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REPORT No. 849

The Transonic Free Flight Range

WALTER K. ROGERS, JR.

BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

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BALLISTIC RESEARCH LABORATORIES

REPORT NO. 849

February 1953

THE TRANSONIC FREE FLIGHT RANGE

Walter K. Rogers, Jr.

Project No. TB3-0108J of the Research and
Development Division, Ordnance Corps

ABERDEEN PROVING GROUND, MARYLAND

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Aberdeen Proving Ground, Md.

THE TRANSONIC FREE FLIGHT RANGE

ABSTRACT

The Transonic Range, developed at the Ballistic Research Laboratories at Aberdeen Proving Ground for ballistic-aerodynamic research has been in full scale operation for approximately three years. Experimental methods, many of which are merely magnifications of similar proven methods used in the smaller Aerodynamics Range, have proven satisfactory. The results obtained give adequate accuracy and are reliable enough to make this range a valuable tool for the free flight testing of missiles and for research pertaining to compressible flow phenomena.

Within this report, the purposes of the Range and the experimental methods used to pursue these purposes are outlined. The range facility itself and its instrumentation are described.

The various records required of the Range are presented with illustrations. Different types of instrumentation for special records are discussed.

The methods of reduction of the raw Range data into final aerodynamic coefficients are briefly described and accuracies given.

Representative samples of data are given in illustrative graphs.

The Appendices contain an outline of the steps and reasoning behind the design of the Transonic Range and a brief description of the Free Flight Aerodynamics Range. Also, numerous photographs and other illustrations are included in this section.

INTRODUCTION

The Transonic Range of the Ballistic Research Laboratories is part of the Free Flight Aerodynamics Branch of the Exterior Ballistics Laboratory. It is an enclosed free-flight range through which missiles are launched that, under usual program conditions, are not restrained or affected by forces other than those normally obtained in flight.

The purposes of this Range are threefold and can be listed as follows:

1. To obtain measurements of aerodynamic coefficients from free flight of projectiles up to 8 inches in diameter.

2. To provide an accurate instrument with which to investigate the causes of dispersion of projectiles.

3. To obtain data of flow characteristics from the subsonic through the transonic and on into the supersonic regions of velocity.

The Transonic Range has many predecessors and contemporaries as a free-flight range. The first such Range is believed to have been built at the National Physical Laboratory in England. The second Range was built and used in this country at Aberdeen by R. H. Kent, now Associate Technical Director of the Ballistic Research Laboratories. Along the same lines as Mr. Kent's range, was the Free Flight Aerodynamics Range in the basement of the Ballistic Research Laboratories built under the direction of Dr. A. [illegible] Charters. Dr. Charters was largely responsible for the prese[illegible] [illegible]mentation of the smaller range and the design and building of [illegible] [illegible] range.

There are a number of contemporary ranges in America such as:

1. [illegible]surized range at Aberdeen Proving Ground.

2. [illegible]anges, one pressurized and one large spark photo range, at Nav[illegible] [illegible]nance Laboratory at Silver Spring, Maryland.

3. A range at Naval Proving Ground at Dahlgren, Virginia.

4. A large range at Naval Ordnance Test Station at Inyokern, Cal[illegible]ia.

5. A range and wind tunnel combination at the N.A.C.A. Ames Laboratory in California.

In the free flight ranges the usual ballistics problem is worked in reverse. Usually one obtains aerodynamic coefficients from a wind tunnel, calculates them from theory or makes estimates from previous experience or data available on similar shapes. Having this information

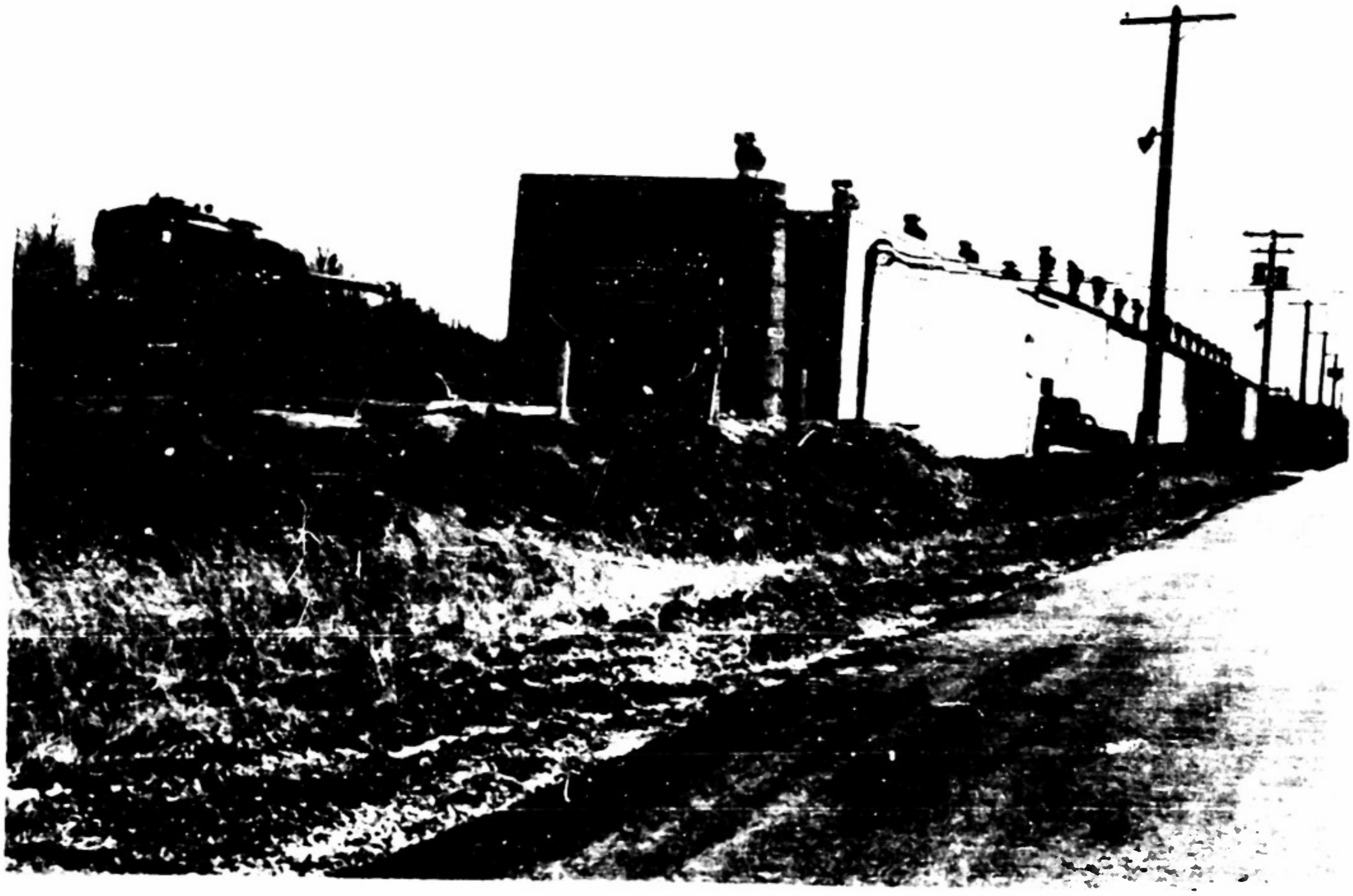

FIG. 1. Exterior of Range View Downrange From Firing Ramp.

and using ballistic theory, one calculates the motions and trajectory of the missile. However, in the free-flight method, one observes the motions of the projectile and with proper ballistic theory calculates the aerodynamic forces and coefficients that would have been necessary to produce such a motion.

DESCRIPTION OF THE TRANSONIC RANGE FACILITY

The Transonic Range was designed in 1944 and completed in 1947. The instrumentation was completed for full scale operation in the summer of 1950.

The Range is 750 feet long and 24 x 24 feet in cross section. The exterior of the Range is seen in Figure 1. One-third of the building, nearest the gun position, is of reinforced concrete while the remainder is of sheet metal on a steel frame construction.

The projectile to be tested is launched from a gun or launcher (such as the tank and gun in the photograph). It passes through the opening in the large concrete blast shield and then into the enclosed range.

In order to illustrate the instrumentation within the Range building, a schematic drawing of the set-up is presented in Figure 2.

The projectile, as located in space, is seen at the center with spark generator and camera combinations on the right and bottom. A close view of a spark generator and a camera in a pit is seen in Figure 9, Appendix B.

The sparks are generated in confined air gaps of the Libessart type which approximate a point source. A picture of the mechanism is found in Figure 10, Appendix B. The voltage used is 15 KV and capacitance 0.25 microfarad. These sparks project shadows of the projectile and the surrounding flow phenomena upon the large beaded screens at the left and top. The cameras take pictures of the shadows projected on these screens. The cameras are equipped with f 2.5, 7 inch focal length lenses.

In order to locate the projectile in space a rectilinear coordinate system has been established throughout the Range. The coordinate axes are: X, horizontal and normal to the plane of fire; Y, vertical; and Z horizontal and along the line of fire. Consequently, the XZ plane is horizontal, the YZ plane vertical, and the intersection of both, the Z axis, passes approximately through the gun muzzle. The XY plane extends transverse to the trajectory across the height and width of the Range building.

These major coordinate planes are located in the spark photographs by the shadows of wires placed in front of the screens as shown in the

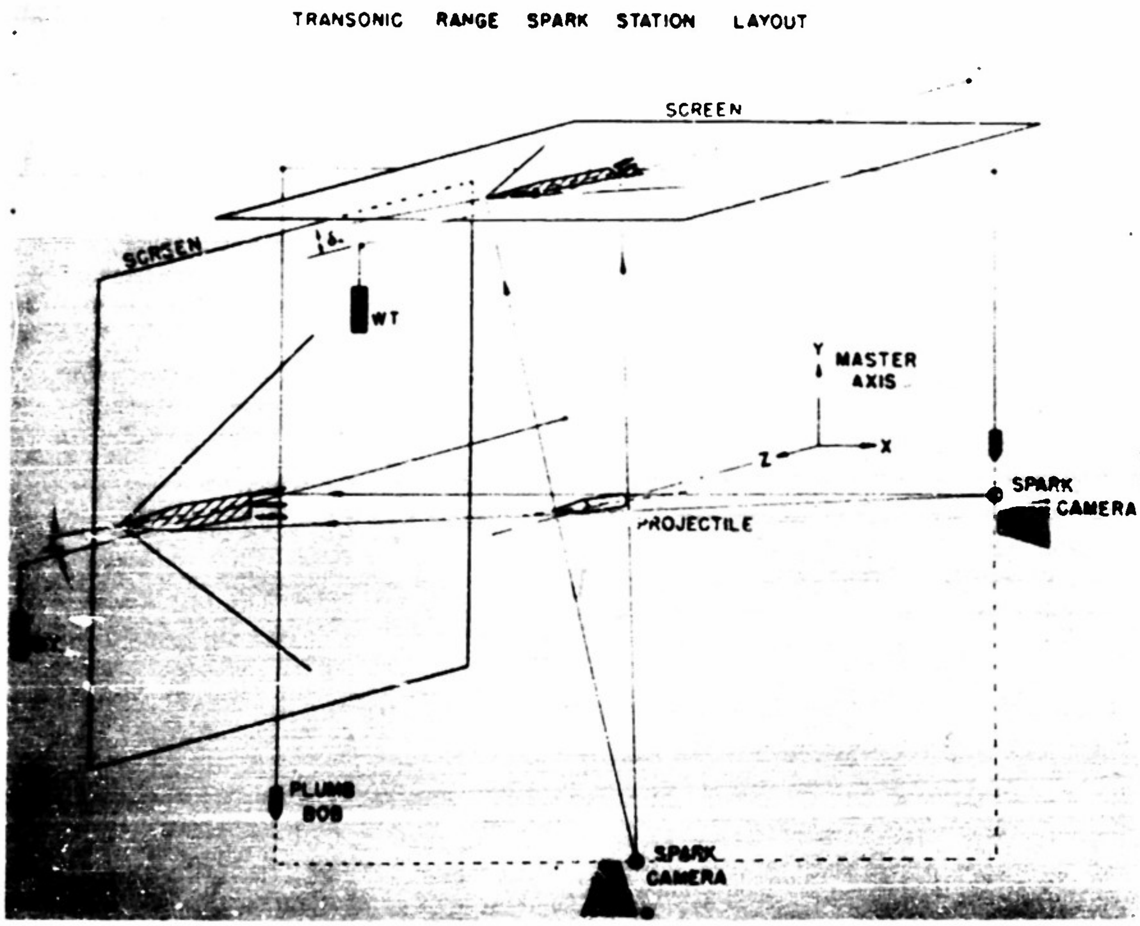

FIG. 2. Schematic Drawing of Instrumentation Set-Up In Range.

schematic drawing. Wires parallel to the Z axis are located in front of the wall and ceiling screens in the XZ and YZ planes respectively. An XY plane is established at each station by placing a wire circumferentially around the Range along the intersections of the XY plane with the wall and ceiling screens. The wall and pit spark gaps are placed in this same XY plane.

A careful survey is required* to place these fiducial wires. The XZ plane is determined with a precision level. The YZ plane is determined by stretching a wire the entire length of the Range and projecting the resulting line down upon secondary bench marks secured in the floor as seen in Figure 11, Appendix B. These bench marks also locate the XY plane. Their distance along the Range is measured with great accuracy by precision tape survey. The spark gaps and cameras are elevated in an XY plane by means of a precision theodolite. See Figure 12, Appendix B.

Figure 3 is a photograph of the interior of the Transonic Range showing the full complement of 25 stations arranged in five groups of five stations each. The details of the apparatus can be recognized from the description given in the discussion of the schematic drawing. The only additional features to be noted are the solenoid coils placed along the trajectory, one just ahead of each station. The projectile is magnetized before firing and its passage through a coil generates a signal which is then amplified and delayed. This signal is used to trigger the spark at the instant the projectile is opposite the approximate center of the screen. These coils are an interim solution for triggering the sparks. Large photo-electric screens are now on contract. These are expected to increase efficiency and also, because of their distance from the trajectory, to be less subject to damage.

The equipment on the floor of the Range was put into pits for protection and convenience. The spacing of stations was dictated by the field of view of the camera and also by the sensitivity of the coils to adjacent stations. The stations within each group are 20 feet apart with a 70 foot interval between groups. Thus, between first station and last there are 680 feet.

In Figure 13, Appendix B, another type of station set-up used in the Transonic Range is illustrated. This apparatus is for taking a direct photograph of a projectile in flight. This method is not always successful toward the exit end of the Range where greater dispersion causes the depth of field to be large. The direct photography method however, is especially useful as auxiliary instrumentation to show the external condition of projectiles.

The second purpose of the Range, i.e., data of detailed flow characteristics, is partially satisfied by the regular spark records. However, another piece of specialized instrumentation has been developed to further this purpose. It is called a mosaic. As this name indicates,

* The primary ideas for these survey methods were furnished by Mr. Robert L. Rowe of the Free Flight Aerodynamic Branch.

FIG. 3. Interior of Transonic Range.

it consists of a series of large 11" x 14" photographic plates laid out together on a table top placed just below the calculated trajectory. A spark source, located above these plates is triggered in the same way as the standard stations and the large "mosaic" picture is obtained. This picture shows flow detail in such a size as to be easily studied for small effects. When trajectories can be closely estimated then the distance from spark to plates in this set-up can be shortened to perhaps as little as five feet. This allows the use of a fast and less intense spark and results in sharper detail than the usual shadow station already described. A photograph of one of these "mosaic" tables is seen in Figure 15, Appendix B.

Both the control for the firings, and the recording mechanism for the timing data, are found in the Instrument Building located some 1000 feet from the Range itself. This building is shown in Figure 4. It contains an office, photographic dark rooms, a model and instrument shop, an electronics laboratory and a chronograph room. This latter room is shown in Figure 17, Appendix B. It contains 1.6 megacycle counters with an accuracy of approximately 1/6 microsecond. The pulses to the counters are received over coaxial cables from the Range. Also shown in the photograph is a drum type cathode ray chronograph camera. Millisecond signals are sent from a frequency standard at the oscilloscope screen and photographed on film which is wrapped around a high speed drum. Intermittent pulses are also photographed from the Range sparks. These are found interspersed with the calibrated millisecond pips on the film and can then be measured on a micro-comparator. Figure 17 also shows a small control console which operates cameras, a bias control and a safety control for the gun.

Associated with the Free Flight Aerodynamics Branch are two model shops - one at the Transonic Range and one in the main Ballistic Research Laboratories building. These shops manufacture most of the models for research and in many cases models for contracting agencies or parts of experimental service rounds.

The Range is further served by a Physical Measurements Section which measures physical properties of projectiles such as moments of inertia, center of gravity position, and other pertinent characteristics.

PREPARATION FOR AND FIRING OF A PROGRAM

The above general description of the Range facilities will be expanded below as it applies to the actual preparation for and firing of a program at the Transonic Range.

The model shops, after receiving the approved designs for projectiles, manufactures the models. Employed in the model making are the usual precision tool makers' tools with a few special purpose instruments such as an air tracer attachment for the lathes which

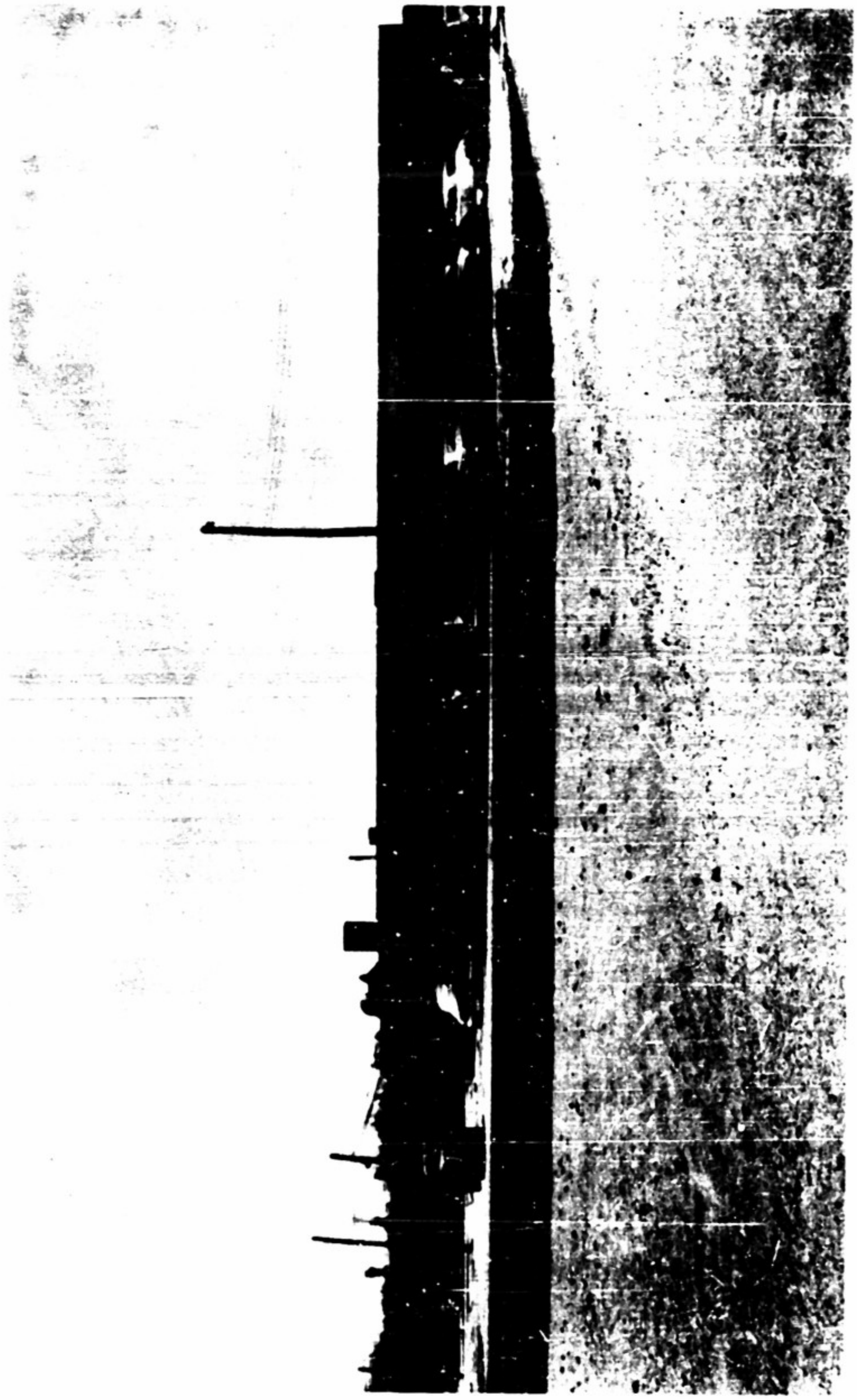

FIG. 4. Exterior of Instrument Building.

automatically follows pre-ground templates of missile contour and a precision contour grinder with an accuracy of $\pm.0003"$, for use in grinding these model contour templates.

After the models are manufactured, they are taken to the Physical Measurements Section for measurements. The moments of inertia, both transverse and axial are determined on a torsion pendulum by comparison with known test masses. The periods are measured by means of electronic timing. The timing signal is produced and recorded through a photo-cell-optical-counter combination. A 155mm standard shell is shown in a torsion pendulum in Figure 22, Appendix B.

After the preliminary manufacture and measurements have been completed, the means of launching must be determined. To date all launchings have been made from breech loading guns. Some projectiles, because of external configuration, maximum pressure limits, required spin and protection of surface finish, may require special individual launching devices. These devices are usually called sabots. Their purpose is to protect the model from undesirable launching conditions and to give sufficient obturation of propellant pressures to insure the required velocity and successful flight into the enclosed Range. Each sabot is designed to fit a particular type of projectile.

The expected trajectory or flight path is calculated by standard methods and the spark trigger coils are adjusted to fit this path. As previously mentioned, each spark unit contains a delay system which must be adjusted to the expected velocity to allow the projectile to proceed to a point opposite the center of the reflective screen before the spark is discharged.

After all of the above preparations have been made, a systematic firing procedure is carried out. The cameras are loaded with photographic plates. All personnel are cleared from the possible danger areas. The projectile and propellant are loaded into the gun. From the Instrument Building the cameras are opened and a bias control operated which allows the spark stations to operate on the pulse from the trigger coils. The gun is fired, cameras are closed and the Range personnel collect the plates for processing in the photographic dark room.

RECORDS PRODUCED BY THE RANGE

The basic records obtained in the Transonic Range are the spark shadowgraphs on 4" x 5" photographic plates, a print of which is presented in Figure 5. For those who are not familiar with this type of photograph it might be noted that the blurred image is the projectile

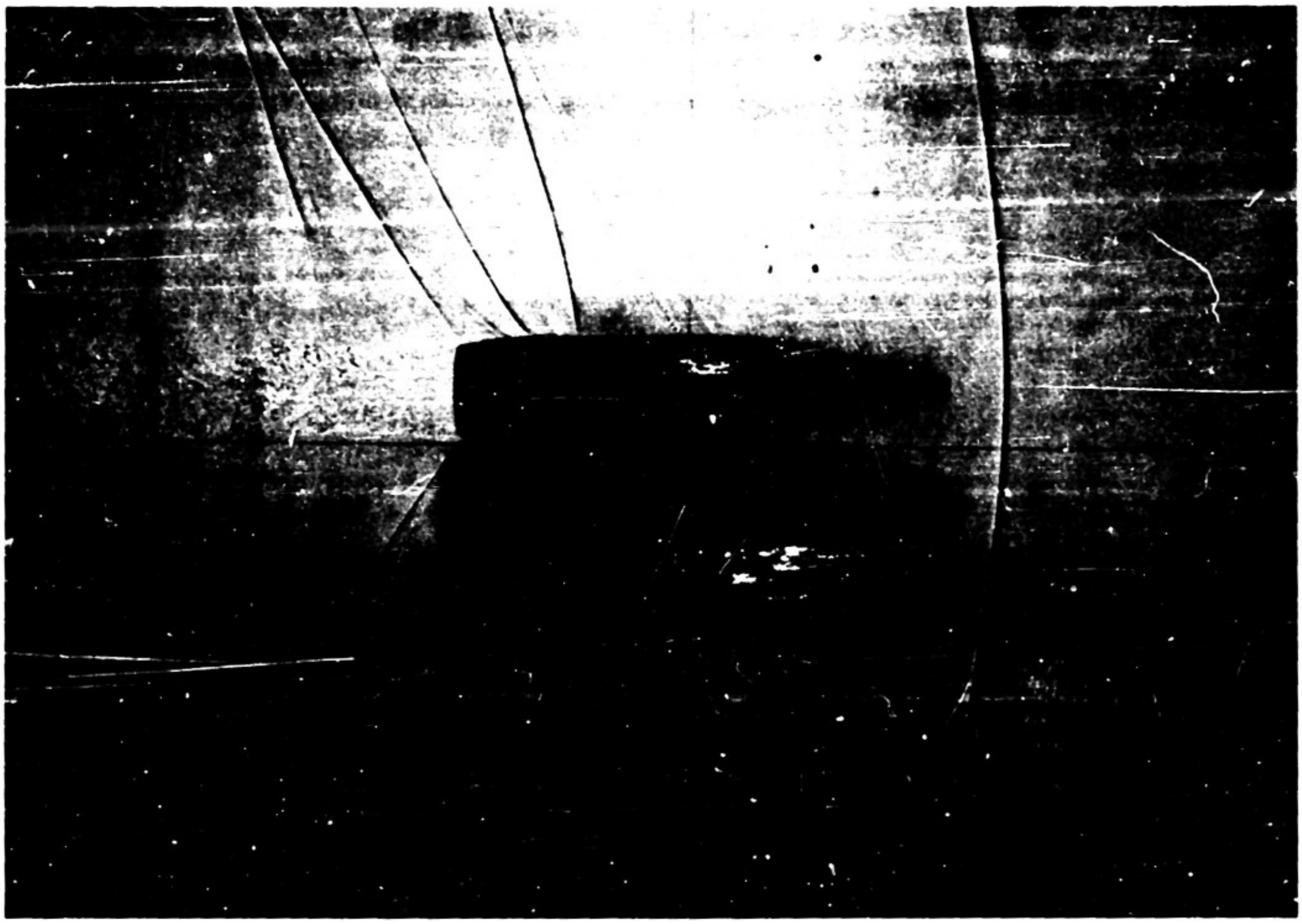

FIG. 5. Shadowgraph. 105mm Projectile.
Velocity: Approx. 1192 ft/sec.
Mach No.: Approx. 1.06

itself. The sharp, black silhouette with the attached flow phenomena* is the shadow of the projectile on the screen. The shadows of the fiducial wires which define the coordinate planes can be seen. Other examples are shown in Figures 18, 20, and 21, Appendix B.

The second type of record is the direct photograph or micro-flash picture. Examples of this type are Figures 14 and 19 of Appendix B. In both examples there is a spiral painted on the ogive of the projectile. Measurements of this spiral, on a succession of micro-flash pictures taken at appropriately spaced stations, result in a reasonably accurate determination of axial spin rate. These pictures show no flow phenomena but are very valuable for determining possible firing damage to missiles which might cause erratic flights in the Range.

Another type of photographic record, also discussed previously, is the large mosaic or multi-shadowgraph. A full-sized example is too large for this report. However, a picture of this type of record is presented in Figure 16, Appendix B.

Besides the photographic records, the time intervals are recorded on the counters and can then be read and copied by Range personnel. At present twelve stations are wired to send timing signals.

REDUCTION PROCEDURE

The Range records are processed by the Data Reduction Section to calculate those aerodynamic forces and moments which are related to the motions of the missile as observed in the photographs. As has been previously described, the plates, shown in Figures 5, 18, 20, and 21, contain fiducial marks or wires to form a YZ reference system on the wall plate and an XZ reference on the floor plate. These plates are placed on an optical comparator[1]. It is possible to locate some point on the projectile and measure its distance from the reference wires. See Figure 25 for plots of x and y vs. z of a representative example. The angles of inclination of the missile's axis to the wires are also recorded. Now, knowing both the physical properties of the projectile and the geometry of the Range, the position of the center of gravity and the inclination of the axis in space are determined.

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* The appearance of the flow phenomena in a shadowgraph such as Figure 5 might be explained in the following manner. The intensity at the photographic screen of the light which passed through the air around the projectile is a function of the density variation in the air. The density gradient in the disturbed flow causes a deflection of the light rays in the direction of the gradient. This refraction of the light causes a dark line or lessening of the light intensity at the front of the shock wave and a light line or buildup of light at the rear of the wave.

1. The optical comparator (shown in Figure 23, Appendix B) gives a magnification of 6-9 and provides a linear measurement accuracy of .001 inch and an angular accuracy of one minute.

Through the last 20 to 30 years the theories of the yawing motion of the projectile in free flight have been developed by R. H. Fowler, E. G. Gallop, E. N. H. Lock and Richmond, R. H. Kent, J. L. Kelley and E. J. McShane and others. Application of these theories to the reduction of data from a free flight range is given in BRL Report 684[1]. A modification and amplification of this work is being prepared.

Time and yaw are both continuous functions of distance along the Range, but the values of these functions are controlled by the aerodynamic properties of the missile.

The drag coefficient, K_D (neglecting yaw effects), is easily determined. It has been found both theoretically and experimentally that over a short range, the time position of the projectile can adequately be expressed as a cubic polynomial in distance.

$$t = a_o + a_1 (z - z_m) + a_2 (z - z_m)^2 + a_3 (z - z_m)^3$$

t = observed time, seconds

$z - z_m$ = distance from mid-range (z_m)

By the use of a least squares fit to the experimental observations, the coefficients in this equation may be determined and the velocity and retardation at the center of the range are:

$$V = \frac{1}{a_1}, \quad \frac{dV}{dt} = \frac{-2a_2}{a_1^{\,3}}$$

The product of retardation and mass gives the Drag Force and the drag coefficient

$$K_D = \frac{\text{Drag Force}}{\rho d^2 v^2} = \frac{m}{\rho d^2} \frac{2a_2}{a_1},$$

where ρ = air density in slugs

d = diameter of projectile ft.

v = velocity ft./sec.

m = mass

The yawing motion is approximated by a damped epicycle with slowly varying rates[2]. In order to handle the problem the assumption is usually made that over a short distance (namely, 80' in the Transonic

1. Turetsky, R. - BRL Report No. 684, "Reduction of Spark Range Data."

2. See Figure 26 and 27, Appendix B, for an example of plotted epicycle from sample data.

Range) the damping of the arms of the epicycle and the variation of rates are negligible and the yaw of repose is neglected for a first approximation. This leads to the following type formula:

$$\delta_H + i\delta_v = \delta = K_1 e^{i\theta_1} e^{i\phi_1'(z - z^*)} + K_2 e^{i\theta_2} e^{i\phi_1'(z - z^*)}$$

where δ = yaw with respect to a tangent to the actual trajectory

K_1 = nutational or fast rotating arm (outer arm)

K_2 = precessional or slow rotating arm (inner arm)

$\theta_{1,2}$ = phase angles of above arms

$\phi'_{1,2}$ = rotational rates of arms

z = distance down range

z^* = position of projectile at center station, within each group.

To add some clarity to the above statements and formula, Figure 6 is presented to give a geometrical interpretation[1] to the yawing motion. Since the pure epicyclic motion may be constructed of two circular motions, these are shown as the rotation of arm K_2 about the origin at rate ϕ_2' and rotation of K_1 about the end of K_2 arm at the rate ϕ_1'. Thus, any point P on the outer or nutational circle is rotating about a center which is itself rotating about the origin. θ_1 and θ_2 are phase angles of the two radii at z^*.

A first approximation to the above equation may be obtained graphically. This is accomplished by assuming a series of values for the slow rate ϕ_2' and by rotating the yaw vectors at these rates until the end points of these vectors lie in a circle[2]. With the spark stations grouped as they are in the present range set-up, each group of five stations is used to determine one circle and there are five such circles for the complete range. From these individual circles, the parameters ϕ_1', ϕ_2', K_1, K_2, θ_1 and θ_2 are determined.

Having completed the first approximation of the unknowns involved in the yaw equation, the computer proceeds with the second approximation which takes into account damping rates. However, with the rough parameters gained from the first approximation he may proceed directly to the iterative method of differential corrections to these values.

1. Taken from pp. 9, BRL Report No. 684, by R. Turetsky.

2. See Figure 28, Appendix B for an example of a circle obtained from sample data.

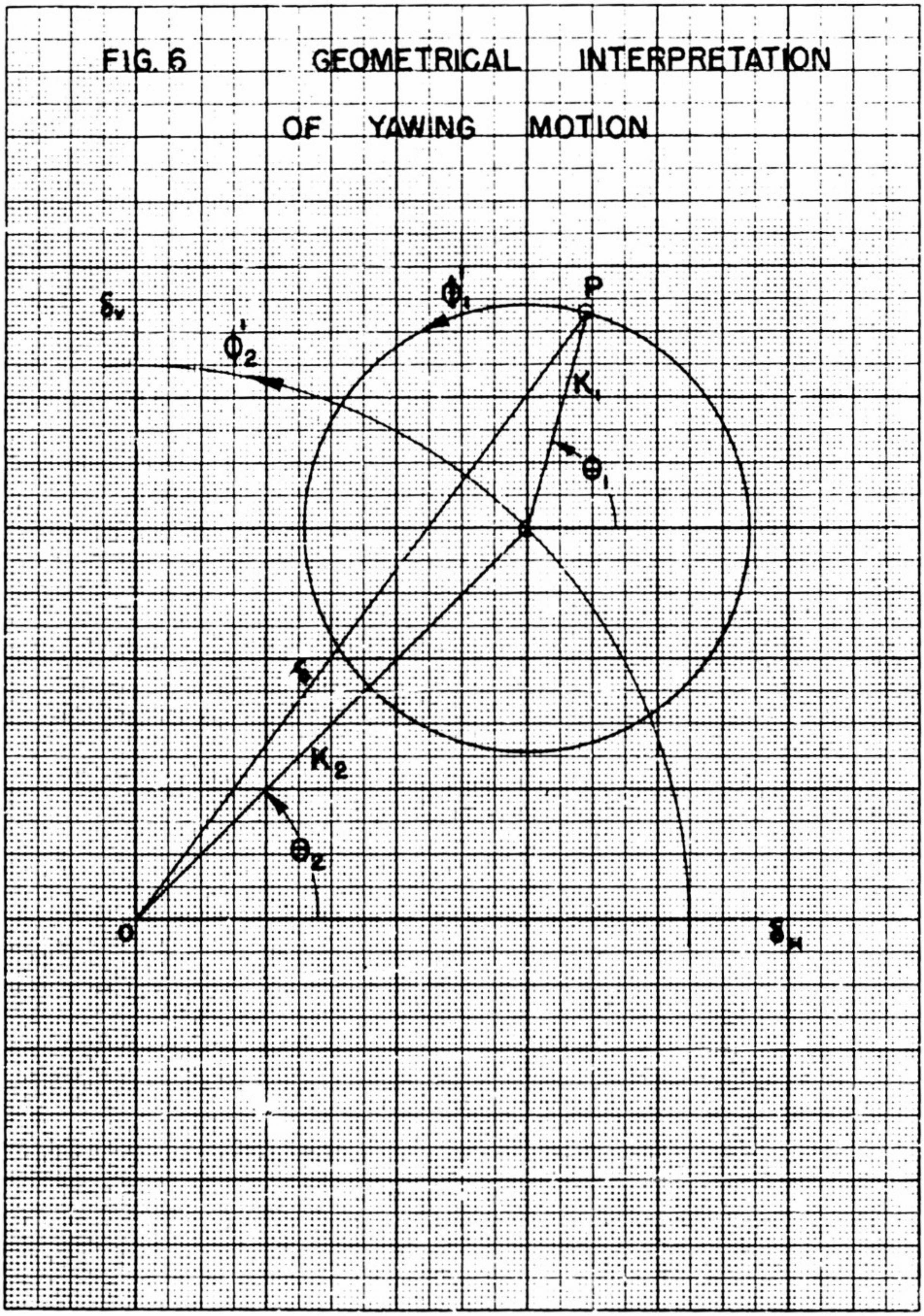

FIG. 6 GEOMETRICAL INTERPRETATION OF YAWING MOTION

This work is usually carried out on one of the high speed computing machines in the Ballistic Research Laboratories, and can be continued until the sum of the squares of the residuals is at a minimum. These differential corrections when added to the initial values give the final values of the desired parameters.

If the computer is successful with the approximations above, he may obtain K_M, the moment coefficient, and K_A, the spin decelerating coefficient directly. However, the lift coefficient K_L must be obtained from either a swerve reduction[1] or from the results of a program in which the center of gravity of the projectile is varied. Once K_L is determined and using parameters obtained in the yaw and drag reduction K_H, the damping moment coefficient and K_T, the magnus torque coefficient, may be obtained.

It is not the intent of this report to go further into the details of a reduction procedure. The three or four reference reports are given for those wishing to go into complete methods.

It may be said that with the present method of reduction, the complete procedure for one round takes one computer approximately one week. Machine methods, however, are now being studied to reduce this time and the reader is referred to another paper[2] which deals with the use of an analogue computer technique. Also under study is a plate measuring machine to further reduce the time required for this laborious task.

ACCURACY OF MEASUREMENTS AND RESULTS

Errors in Transonic Range work might be divided into two classes. The first class of errors includes those that are of a physical nature, while those in the second class are theoretical in that they result from errors in the fit of theories of yawing motion and drag to the experimental data obtained in the range. Both of these classes of errors are discussed below.

Class I. The physical errors are:

a. Tolerances in the physical measurements of the missiles.

b. Errors in the measurement of time and distance in the range itself.

c. Errors in temperature and pressure measurements.

d. Errors in the reading of the data from the photographic plates.

1. Turetsky, Raymond, BRL Report No. 684, "Reduction of Spark Range Data", or Schmidt, L. E., BRL Memo. Report No. 599, "Aerodynamic Coefficients Determined from the Swerve Reduction".

2. Murphy, C. H., BRL Report No. 807, "Analog e Computer Determination of Certain Aerodynamic Coefficients."

The estimated tolerances applied to the physical measurements of missiles are:

Measurement		Tolerance		Means of Measurements
dimensions	length	.002	in.	gage blocks
	diameter	.001	in.	micrometer
weight		.02	lb.	platform, no spring scale
position of the center of gravity		.01	in.	special balance system
moments of inertia		.05	%	torsion pendulum
surface roughness		.00001	in.	profile recorder
angles		1.	min.	optical protractor

A conservative estimate of the time error as measured by the electronic counters is 1×10^{-6} seconds. The distance measurements are made in the Transonic Range to an initial survey accuracy (repeatable) of better than 1×10^{-3} ft. Present conditions, however, in the metal, uninsulated range building do not allow this accuracy to hold over long periods of time due to expansion and contraction of the walls of the building itself and also of the concrete pit sides in which the primary bench marks are mounted. Due to the urgency of most programs, an over-all survey can only be made about four times a year.

A study of the effects of the seasonal temperature variations on survey accuracy is being completed and will allow interim corrections to be made. Also a trial system of survey mountings has been tested which will nearly eliminate the effects of the building movement.

There are other errors in the distance measurement in the range which are involved in the spark photographic techniques. There is an error due to spark duration which shows movement of the projectile and results in blurring of the photograph. The spark at present has a duration of about 3×10^{-6} seconds, which for a projectile velocity of 2000 ft./sec., would allow a projectile movement while being photographed of about 1/16 inch. There is also a possible error due to the two sparks at a station not being synchronized. This error would allow the projectile to move further in one of the two pictures and give an inaccuracy in the final space coordinate of the center of gravity. From oscillograph measurements it is found that this error for the average double spark set-up is about 3×10^{-6} seconds, or again approximately 1/16 inch in space.

Errors in air density effect the values of the aerodynamic coefficients either directly or indirectly. In the evaluation of those coefficients in which the air density is a factor, percent errors in this quantity result in equal percent errors in the coefficient values.

The evaluation of the air density in the range is dependent on the pressure and temperature recorded in the range building. Round to round determination of air density indicates a 1% error in this quantity. However, large temperature gradients in the range can cause the absolute values of air density to be as much as 4% in error.

Evaluation of Mach No. in the range is also effected by the magnitude of the temperature gradients and the errors in Mach No. are approximately half of the density errors as given above.

Upon completion of a contract now in progress, the entire range building will be insulated and the range will have radiant heating throughout. To a large extent this will reduce the temperature gradients encountered in the range at present.

The accuracy with which the photographic plates can be read on the optical comparators is about 2×10^{-3} inches in position measurement and 5×10^{-2} degrees for angular measurement. The former error results in about 1/32 inch error in space position.

Class II. The most difficult error to define is the theoretical error of the fit of theory to experimental points. Since the physical errors as discussed above are already included in the experimental data, this error of fit is a measure of the overall efficiency of the theory and range data. Disregarding a few unusual cases where the theories do not fit experiments too well, a magnitude for this total error can be given from experience with range results. The maximum fitting error for the yawing motion is about 1×10^{-1} degrees and for the drag determination, a distance error of about 1×10^{-2} feet.

Experience with range results in the form of aerodynamic coefficients indicates the following error magnitudes:

Coefficient	Estimated Error in Percent
K_D Drag	1
K_L Lift	5
K_M Moment	2
K_H Damping Moment	15
K_T Magnus Torque	15

REPRESENTATIVE DATA

For reasons of classification a single full program will not be presented. Instead a series of illustrative graphs will be given. These data are indicative of what might be expected from the Range programs but should not be used otherwise.

1. In Figure 25, Appendix B, the x and y coordinates of the center of gravity are plotted versus range distance z for a large spin stabilized projectile.

2. Figure 26 and Figure 27 are plots of δ_V versus δ_H for a spin stabilized and a fin stabilized missile, respectively. Seen here are the expected epicycle plots.

3. Figure 28, Appendix B, is a typical plot of the graphical first approximation to the yawing equation in which the five yaw vectors have been rotated by a chosen slow rate ϕ_2'.

4. Figure 29, Appendix B, is a plot of the drag coefficient K_D and the moment coefficient K_M versus Mach No. for a spin stabilized projectile.

5. Figure 30 is a plot of $\delta_V^2 + \delta_H^2$ versus range length z. This plot graphically demonstrates the period of the yawing motion and the fact that the amplitude is damping.

6. Figure 31 is a plot of K_L, the lift coefficient, versus Mach No. for a spin stabilized projectile.

7. Figure 32 is a plot of K_H, the damping moment coefficient and K_T, the magnus torque coefficient versus Mach No.

SUMMARY

Within this report, the Transonic Range, a new ballistic facility, has been presented. It has the following capabilities:

1. It allows the testing of full scale projectiles up to eight inches in diameter.

2. The data obtained at the Range give a history of the motion of these projectiles enabling one to study their aerodynamic properties in free flight.

3. The flow pattern about the projectile is clearly recorded for aerodynamic consideration.

4. Incorporated with the Range facilities is a 1000 yard target to make the study of dispersion possible through a close study of initial conditions and results on the target.

Walter K. Rogers Jr.

WALTER K. ROGERS, JR.

APPENDIX A

DESIGN OF THE TRANSONIC RANGE

In this section, an attempt has been made to enumerate some of the thoughts and plans which were incorporated in the design of the Transonic Range. When this large range was being contemplated in 1944, the smaller Free Flight Aerodynamics Range was already successfully producing data. However, it was desirable to have a range of such a size as to allow the study of the properties of full scale service projectiles in free flight.

In order to use the methods and theories available to obtain desired aerodynamic parameters this new large range should produce certain records. These are listed as:

1. A time distance history which would give drag.

2. A record of the space coordinates of the center of gravity which would give lift.

3. A record in two known planes of the inclination of the axis of the missile. The period of the oscillations so recorded would give data toward the moments and the amplitudes would give damping data.

4. A record, throughout the range, of the flow characteristics to allow aerodynamic study of flow phenomena through the velocity range encountered. From experience, this requirement, though not imperative, was considered very desirable.

To obtain these records, a photographic method seemed most logical. Photographs would give a permanent, accurate record and need not interfere with the projectile's free flight motion.

An enclosed range was considered most efficient for the following reasons:

1. To obtain the accuracy in final aerodynamic coefficients and to obtain those coefficients through the solution of the equations of motion using existing theories, it was considered desirable to have a good density of observations in the initial stages of flight where the yawing motion is usually most pronounced.

2. The instrumentation should be protected from the elements and the range survey must have a good degree of accuracy.

3. The practical consideration of the greater ease of control for photographic techniques in a light tight enclosure.

4. The air would be still and practically constant in its properties.

The design of the enclosed range building was planned in the following manner. Since it was desired to obtain useful information about a missile's aerodynamic properties within the transonic velocity range, the problem of choking was considered. Little was known of this property with the exception that wind tunnels were universally unreliable within certain limits near the speed of sound. Von Karman[1] suggested that a ratio of 10,000/1, cross section of range and projectile, should be sufficient practically to eliminate this effect in the range. Using a 3 inch diameter shell as a basis, this meant that the unobstructed range cross section should be at least 22 x 22 feet[2]. Francis Clauser, a member of the Scientific Advisory Committee for the Ballistic Research Laboratories, has since proved that ranges will choke in much the same fashion as wind tunnels[3].

To obtain more experimental observations, a long range was desirable. It is known[4] that the drag error varies inversely with the square of range length if absolute accuracy of length and time are invariant. Also, the accuracy of length measurement varies only with the first power of total distance. A long range, however, again would restrict the low range of velocities if impacts within the range were considered impractical. Furthermore, dispersion was estimated to vary between the first and second power of the range length. In the smaller Aerodynamics Range the dispersion was found to be normally about 1-1/2 feet at 300 feet from the launcher. Using a possible figure of 700 feet for the large range length this rule would indicate a normal dispersion of about 6 feet.[5] The range length was designed to be 750 feet. Financial considerations, however, played a considerable part in this limit[6].

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1. Th. von Karman, Director of the Guggenheim Aeronautics Laboratory, California Institute of Technology, Pasadena, California.
2. If it is desired to test projectiles at very low velocities then it must be considered that velocity attainable is dependent on the range cross section and length, position of the launching device and allowable proximity of projectile to instrumentation. Furthermore, with high arcing trajectories the photographic techniques are complicated.
3. Francis Clauser, Paper given at Free Flight Symposium, Jet Propulsion Laboratory, entitled "Choking in Free Flight Ranges", 1947.
4. B. G. Karpov, BRL Report No. 658, "Accuracy of Drag Measurements as a Function of Number and Distribution of Timing Stations".
5. This figure for dispersion has proved to be approximately correct.
6. Recent designs under contract will extend this range length to approximately 1170 feet. This will add about 20 more stations of observation.

The design of the apparatus for obtaining data leaned heavily on the experience gained in the smaller, but already successfully proved, Free Flight Aerodynamics Range. It is felt that a brief description of the instrumentation set-up of this range should be included in this report. (See second section of this Appendix)

The difference in requirements for the two ranges was obvious. The projectiles to be fired in this large range could be 8 inches in diameter and 5 feet in length while the maximum size for the smaller range was about 2 inches in diameter and 10 inches in length. The size of the field of view required in this larger range was much greater. As discussed above, the size of clear flight space to satisfy chocking requirements, trajectory, and dispersion was to be about 22 feet x 22 feet.

This difference suggested that direct photography might be used instead of spark, shadow photography. However, the depth of field required by a six foot dispersion and the location of the projectile in space made this impractical. The latter, though not too complicated, would be expensive, requiring each camera to be precision made and mounted and a system of fiducial or reference marks to be placed within the camera and surveyed as such. Also, experience indicated that there was value to be obtained from the shadow photographs in which the compressible flow phenomena could be studied throughout the flight within the range.

Therefore, the use of spark photography in this large range was studied. The desired flow characteristics would be obtained and the dispersion and depth of field problems were lessened. With direct shadow photography, however, the records would be 12 feet square and, due to the large distance involved, an increase in light would be necessary over that obtained from the spark source then in use in the Aerodynamics Range. To reduce these obstacles the following steps were taken: The larger records were impractical but the motion picture analogy solved the problem. A reflective screen was placed at the side and top of the range and an ordinary still camera used in place of the eye of the audience. This technique solved one problem but the second was intensified, since now the light requirement increased. To obtain more light it was necessary to employ higher voltage and capacity. While the aerodynamic range used 6 KV at .5µF, the larger range was to use 15 KV at .25µF. This was accomplished by the use of a confined air gap spark of Libessart type. A picture of this gap is presented in Figure 10, Appendix B. The light was now bright enough to expose a very fast spectroscopic plate to good density but the duration was about 3 microseconds, giving a distance error of about 1/16 inch at a projectile velocity of 2,000 ft./sec.

The Transonic Range was thus designed and completed in 1947 and has, at present, been in successful full-scale operation for about 3 years.

INSTRUMENTATION OF THE FREE FLIGHT AERODYNAMICS RANGE*

A schematic drawing of the Free Flight Aerodynamics Range is presented in Figure 7. The projectile is shown located in space at the center. The spark light source is at the left while the photographic plates are at the right and bottom. The light from the source is reflected in the tilted mirror at the top and thus the shadow of the projectile is projected on both photographic plates.

To locate the projectile in space from the resulting photographs a rectilinear coordinate system was established throughout the range. The coordinate axes being X, horizontal and normal to the line of fire; Y, vertical and z, horizontal and along the line of fire. Consequently the XZ plane is horizontal, the YZ plane is vertical and the intersection of these two planes or the Z axis may be considered as approximately a line passing through the gun muzzle. The XY plane extends transverse to the trajectory and across the height and width of the range building. These major coordinate planes are located in the spark photographs by means of a fiducial bar which can be seen lying with its major axis along the Z axis. Since the photographic plates are slipped under this bar in both vertical and horizontal planes, the reference Z axis is imprinted on each. This bar is also notched so as to designate the XY plane on the plates. The spark source is located in this XY plane.

To clarify this description, a photograph of the interior of this Aerodynamics Range is shown in Figure 8. The details of the schematic drawing Figure 7, may be seen clearly. This range is about 340 feet long and now contains 50 stations. These are necessarily closely spaced and give high density of experimental data and excellent results. An example of the record from this range is given in Figure 24, Appendix B. The reference system does not show in this small print.

The spark sources now in use in this range utilize 6 KV at .12μF. The photographic plates are 11 x 14 inches in size with a fairly fast emulsion. The projectile carries an electrostatic charge or incorporates a magnet to trigger each spark upon passing through a wire pick-up. There is a calibrated delay built into each triggering unit to allow proper positioning of the projectile.

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* See also:

1. "Some Ballistic Contributions to Aerodynamics", A. C. Charters, Journal of the Aeronautical Sciences, Vol. 14, No. 3, p. 155, March 1947.

2. "The Aerodynamic Performance of Small Spheres from Subsonic to High Supersonic Velocities", A. C. Charters and R. N. Thomas, Journal of the Aeronautical Sciences, Vol. 12, No. 4, p. 468, October 1945.

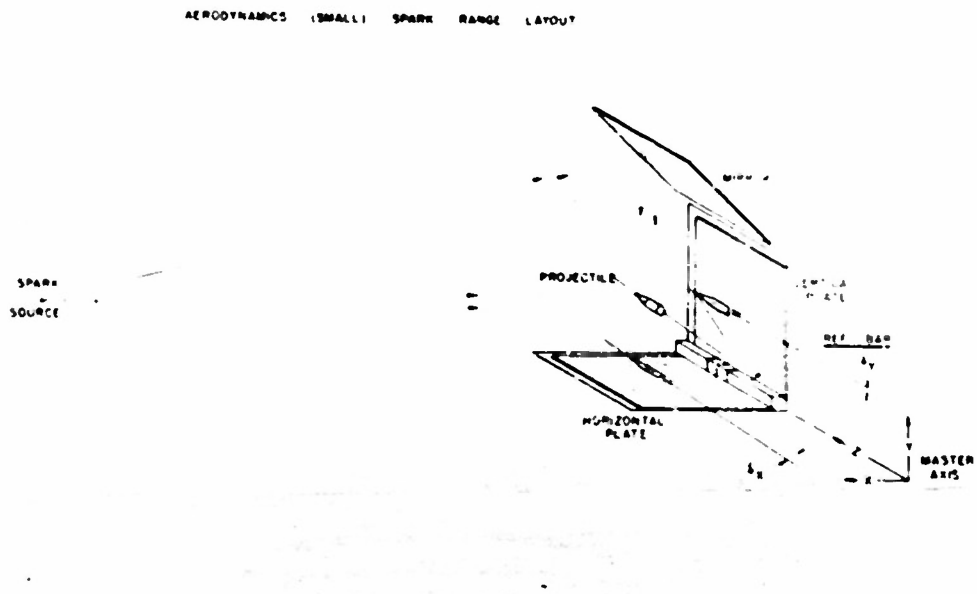


FIG. 7. Schematic Drawing of Instrumentation Set-Up In Small Spark Range.

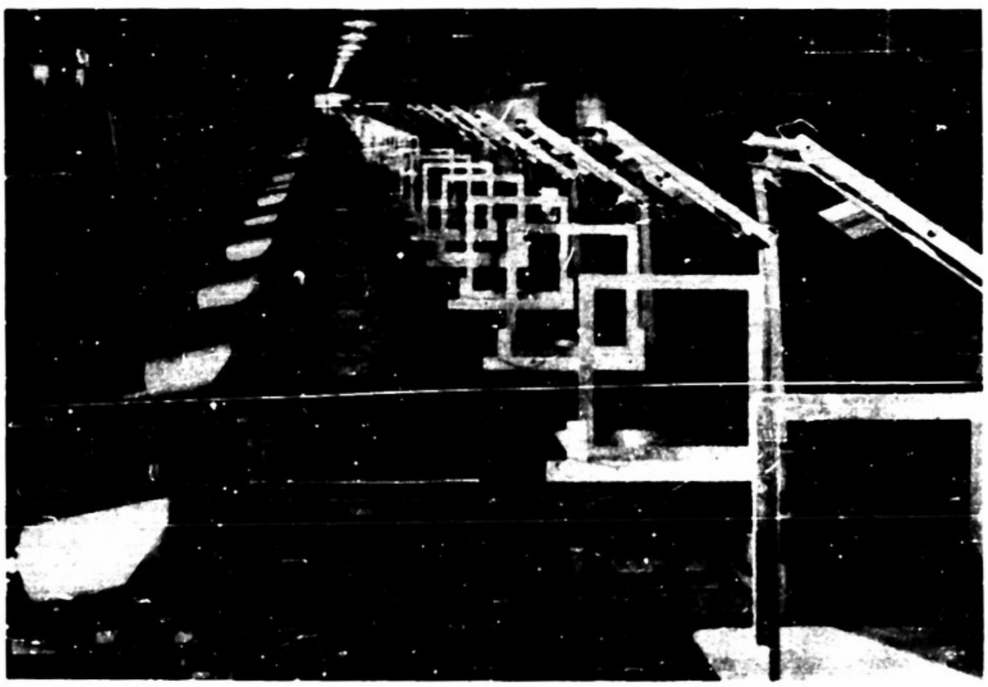


FIG. 8. Interior of Small Spark Range.

APPENDIX B

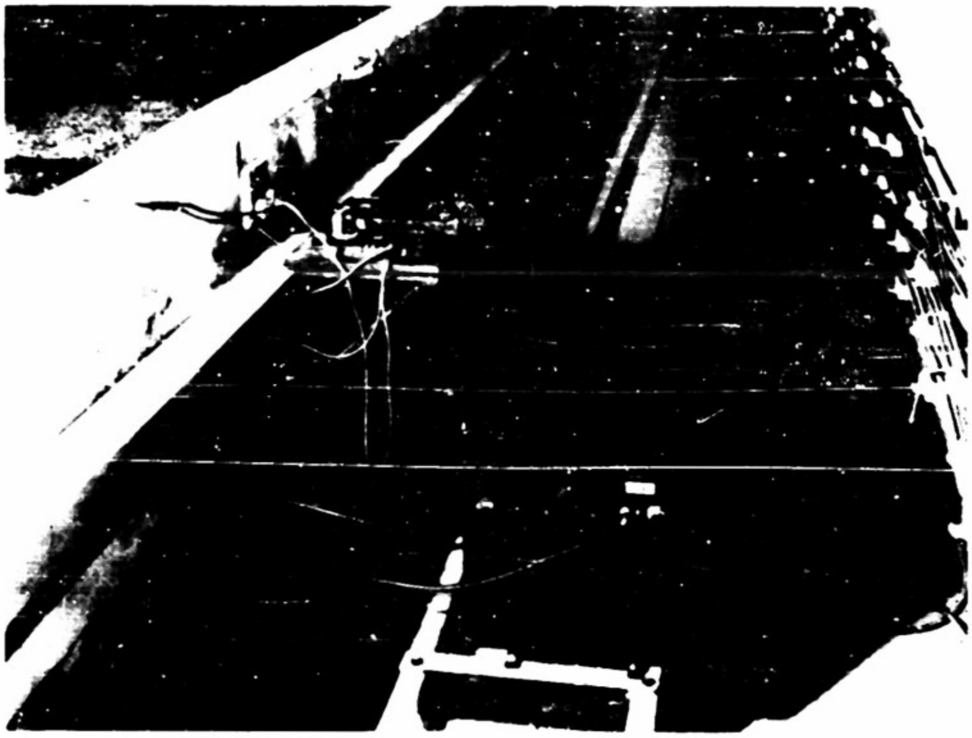


FIG. 9. View of Spark Box (Light Source) and Box Camera Set-Up.

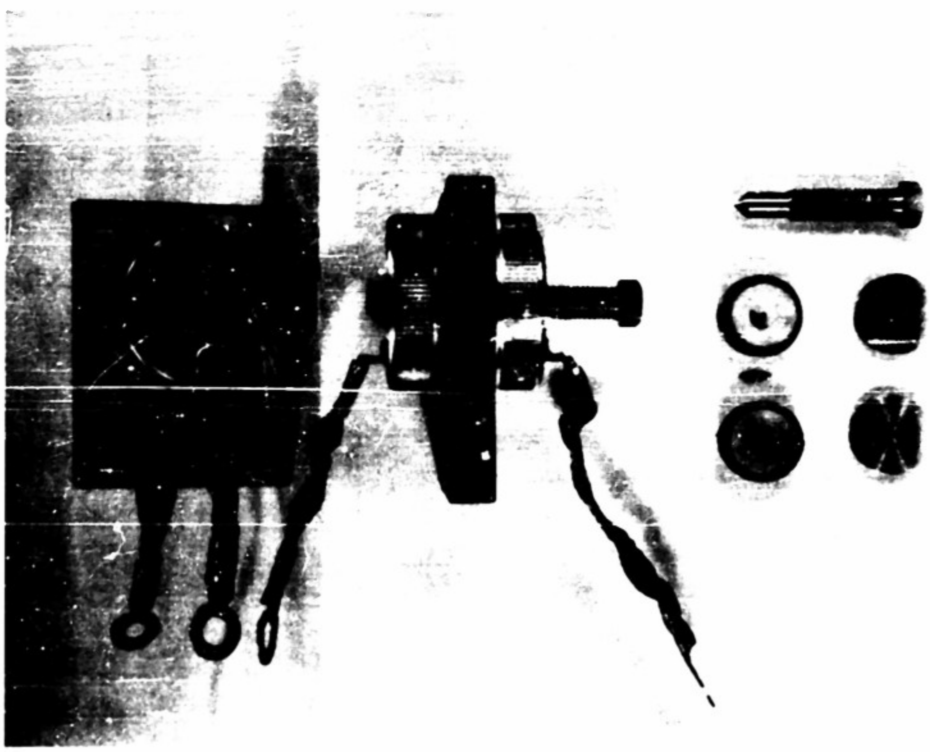


FIG. 10. Confined Airgap Spark. (Libessart Type)

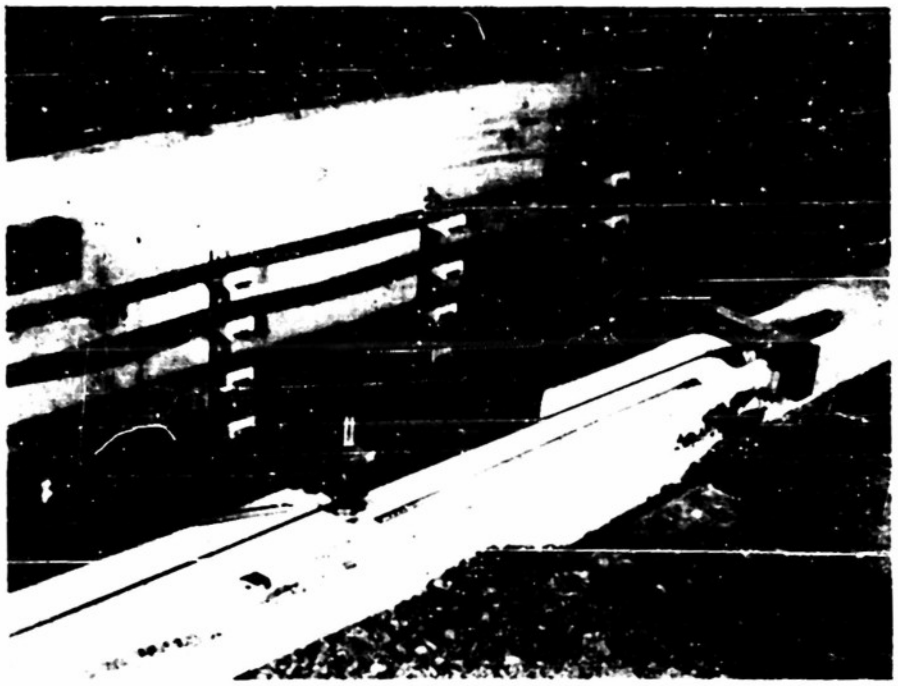


FIG. 11. Range Survey Set-Up. Showing Taping Operation Over Primary Bench Marks.

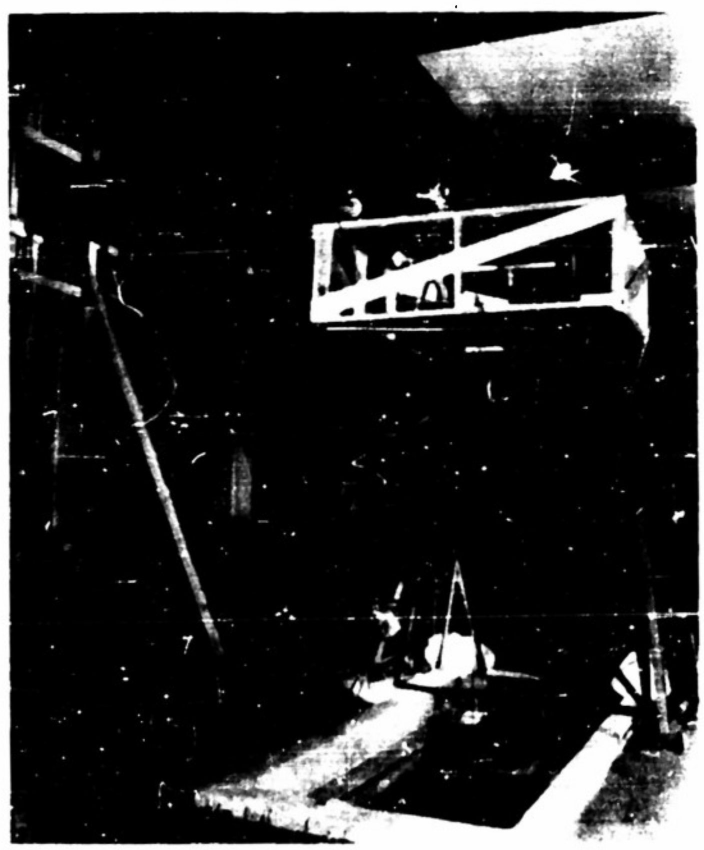


FIG. 12. Range Survey Set-Up. Showing Mobile Stand for Theodolite and Operator.

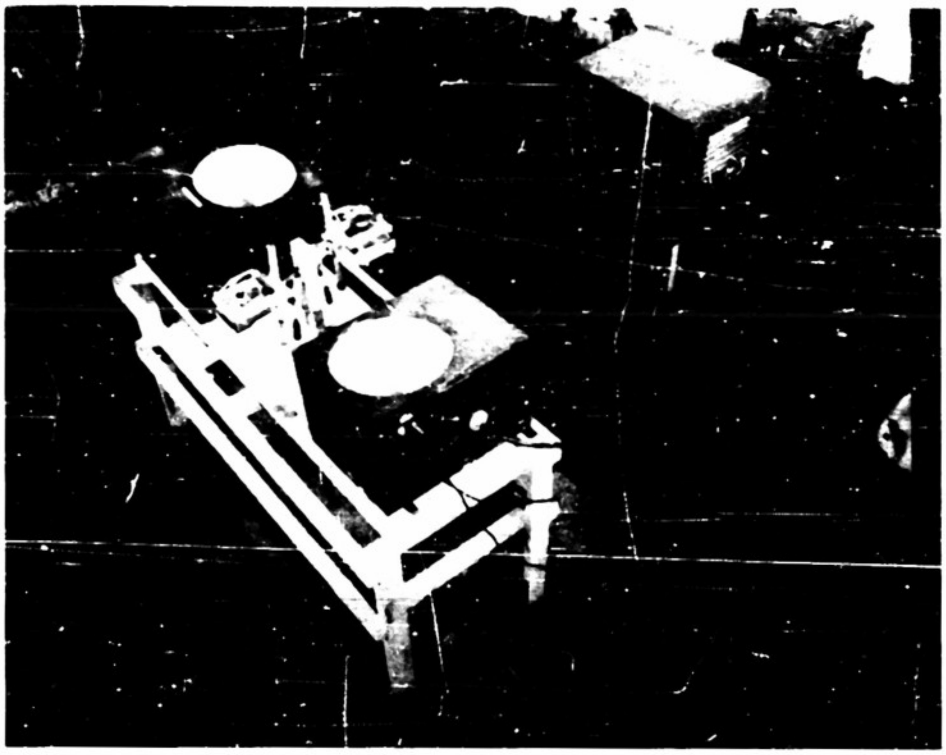


FIG. 13. Microflash (Direct Photography) Set-Up. Showing Double Camera and Spark.

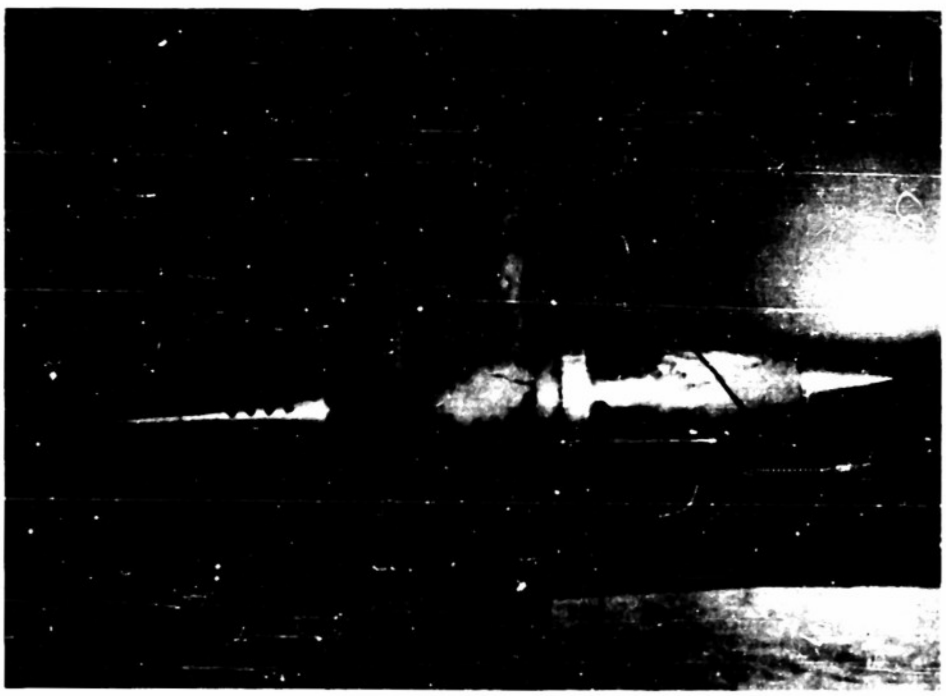


FIG. 14. Microflash (Direct Photograph).
Velocity: Approx. 985 ft/sec.
Mach No.: Approx. .88

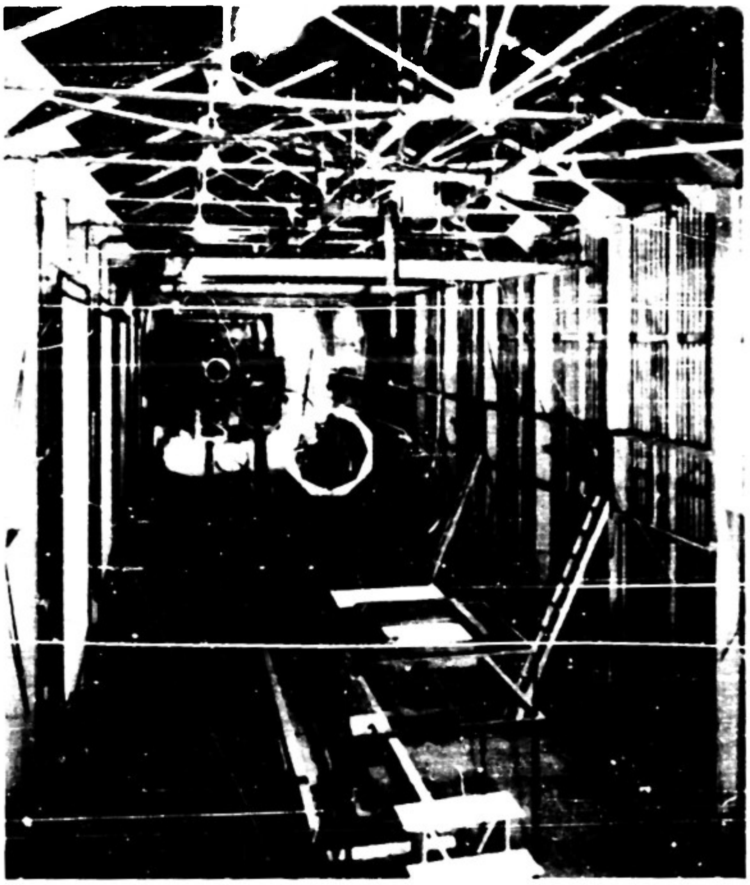


FIG. 15. Mosaic (Multiple Plate) Set-Up. Showing Small Spark in Ceiling Above Plate Table.

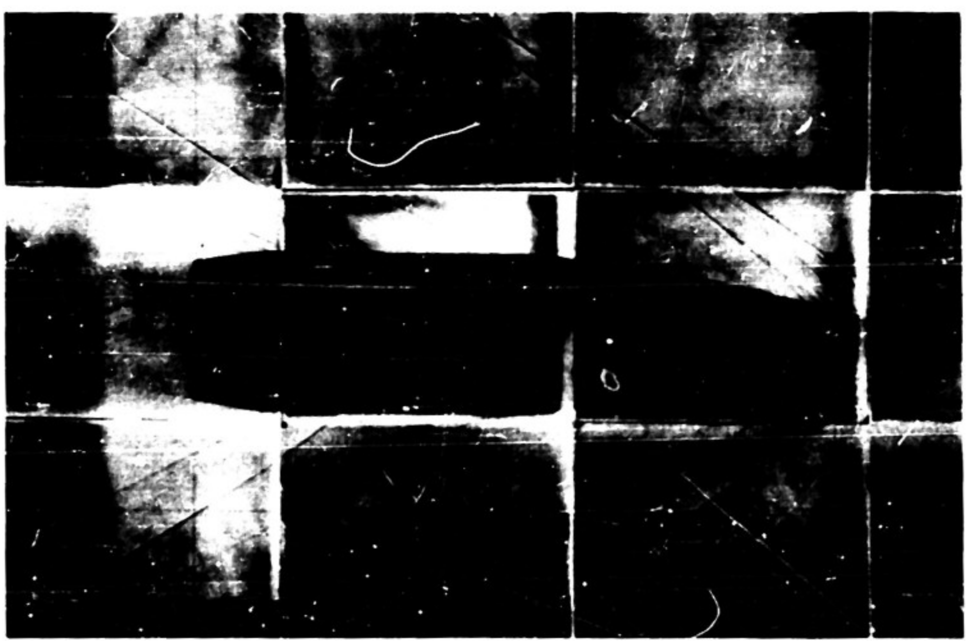


FIG. 16. Large Mosaic (Multiple Plate). Shadowgraph of 155mm Shell.
Velocity: Approx. 2140 ft/sec.
Mach No.: Approx. 1.91

FIG. 17. Interior of Chronograph Room. Showing Counter Chronograph, Control Panel & Drum Oscillograph, Camera Chronograph.

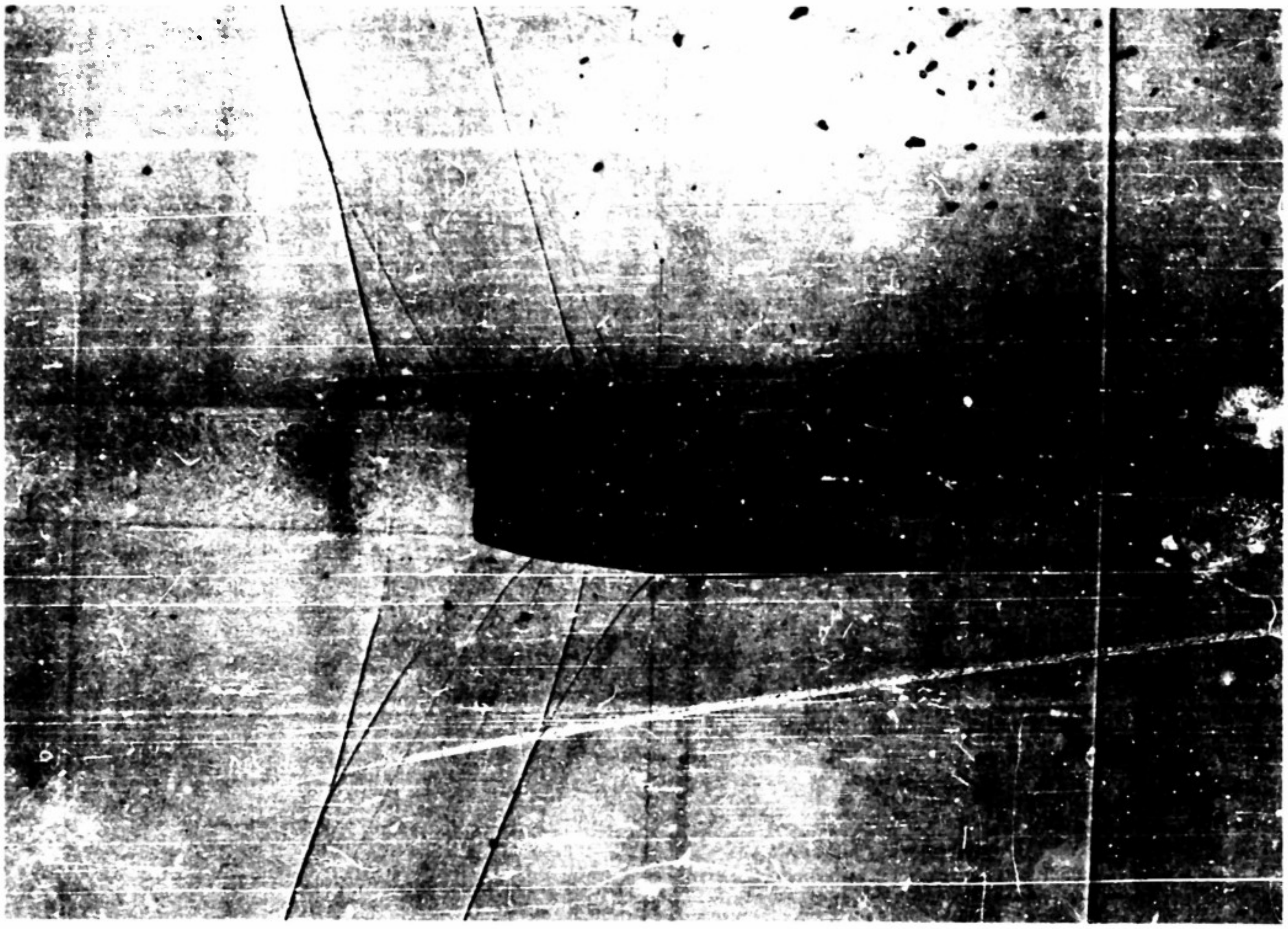


FIG. 18. 155mm Shell in Shadowgraph.
Velocity: Approx. 1130 ft/sec.
Mach No.: Approx. 1.01

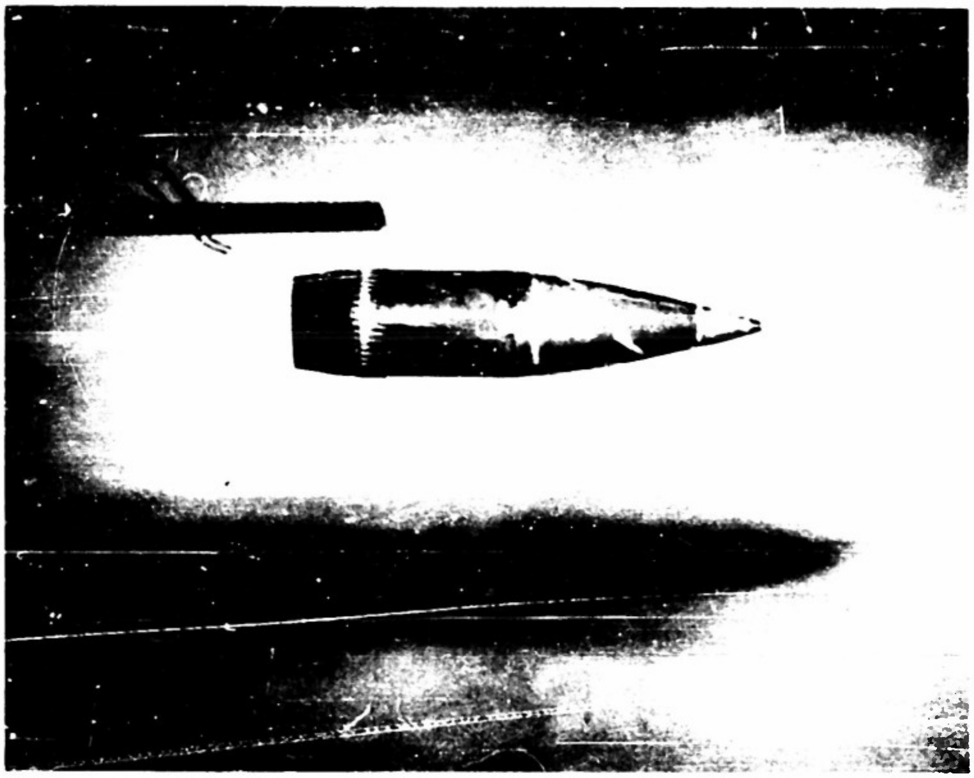


FIG. 19. Microflash (Direct Photograph). 155mm. Projectile.
Velocity: Approx. 1300 ft/sec.
Mach No.: Approx. 1.16

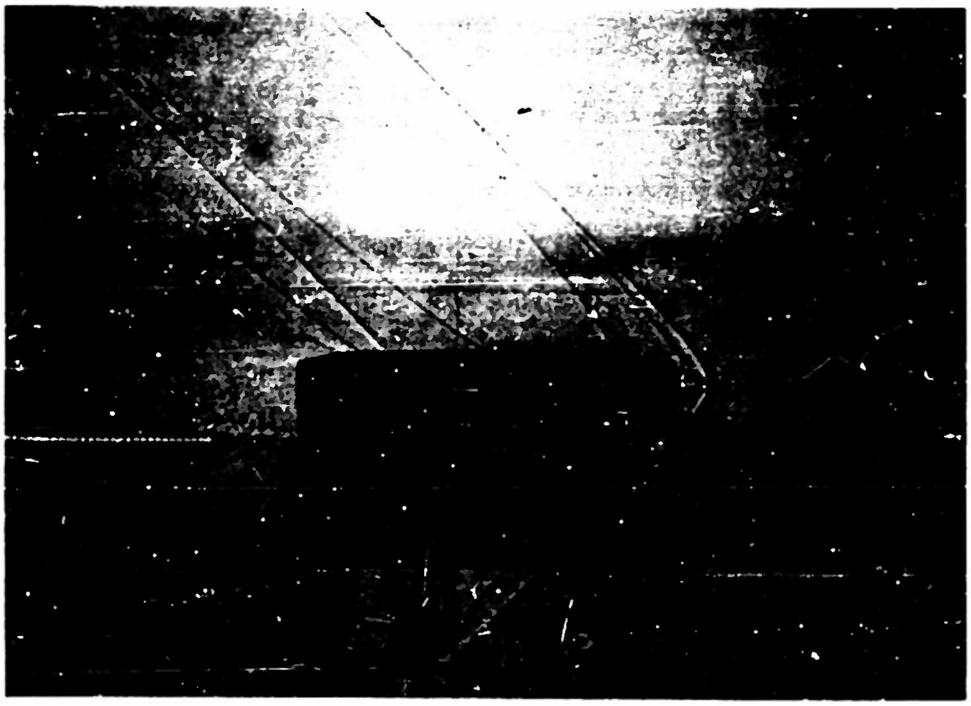


FIG. 20. Shadowgraph of 105mm Projectile.
Velocity: Approx. 1447 ft/sec.
Mach No.: Approx. 1.29

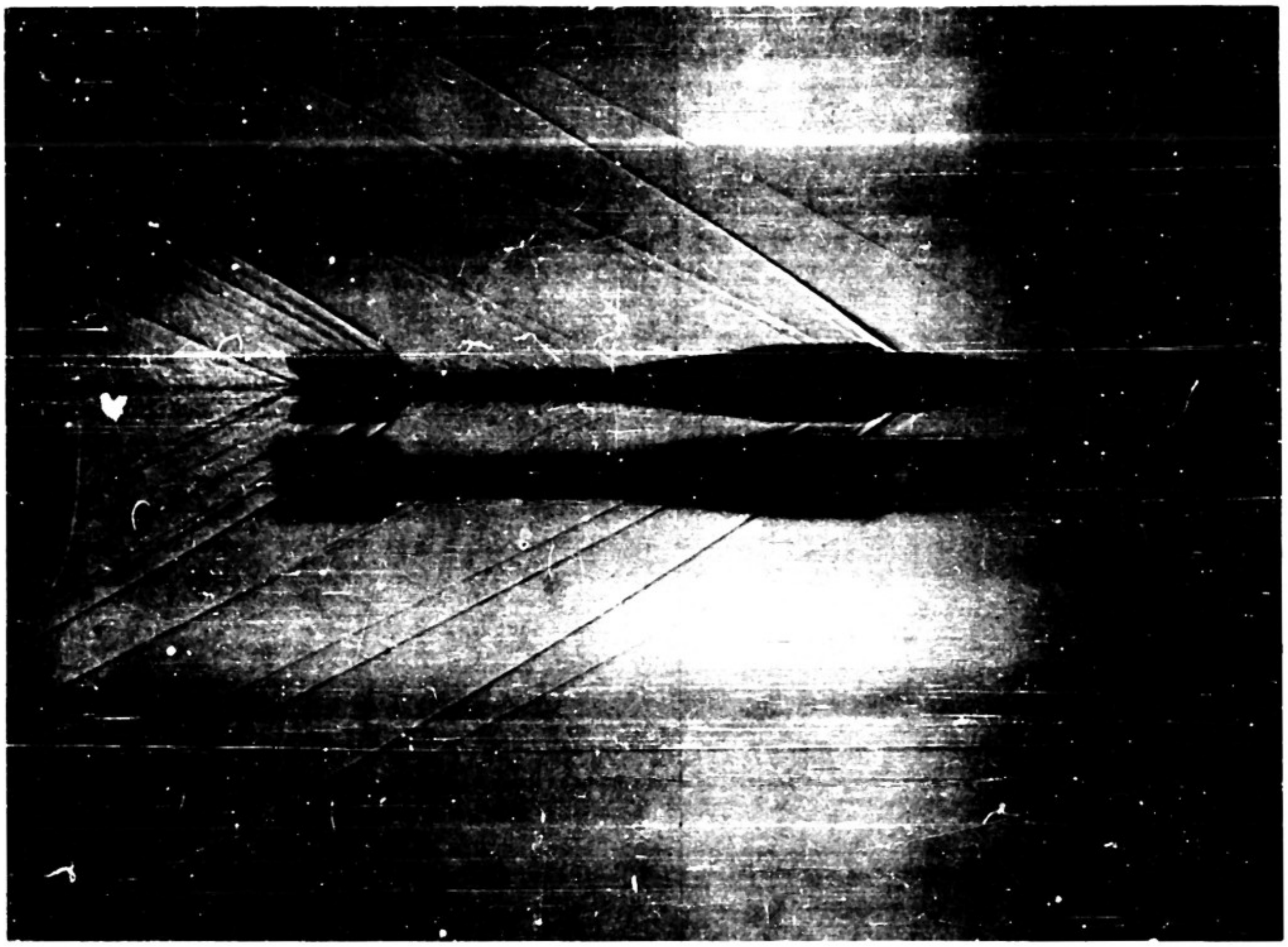


FIG. 21. Shadowgraph. 90mm Projectile With Special Research Cone for Boundary Layer Transition Study. Velocity: Approx. 2414 ft/sec. Mach No.: Approx. 2.15

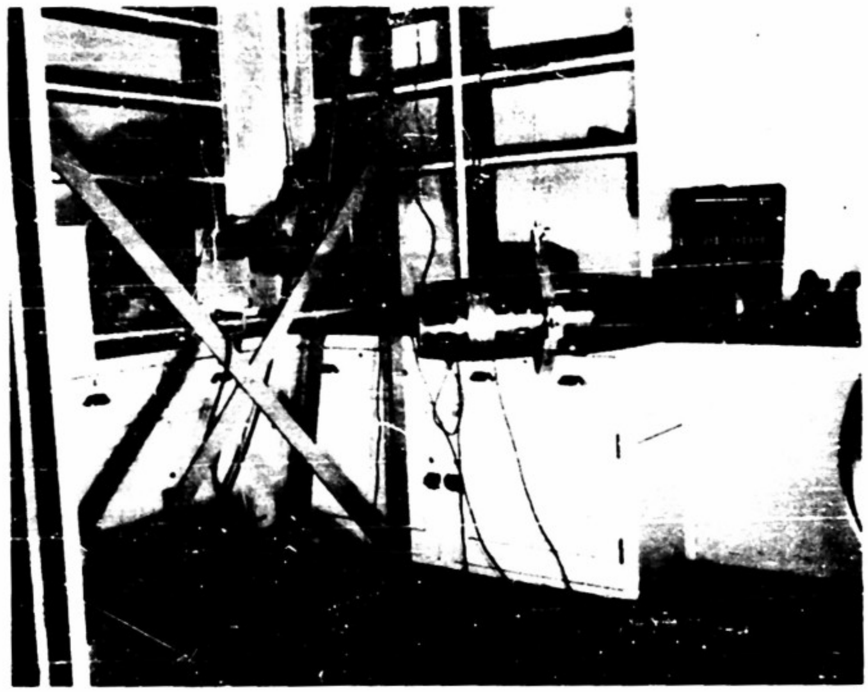


FIG. 22. Torsion Pendulum Physical Measurements Section. (155mm Shell Suspended).

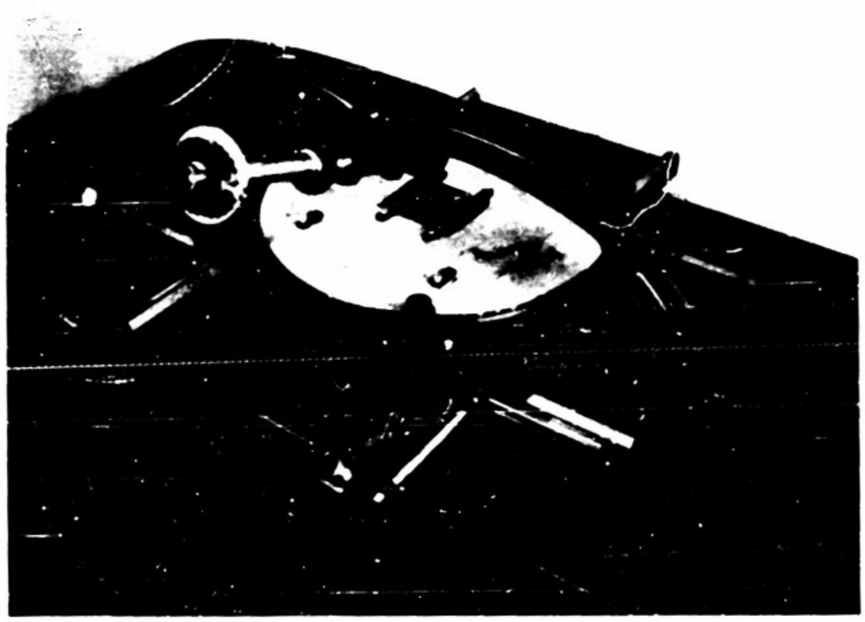


FIG. 23. Optical Comparator, Reduction Section.

FIG. 24. Shadowgraph - Small Range Example Cal. 50 Cone - Cylinder Research.
Velocity: Approx. 1900 ft/sec.
Mach No.: Approx. 1.69

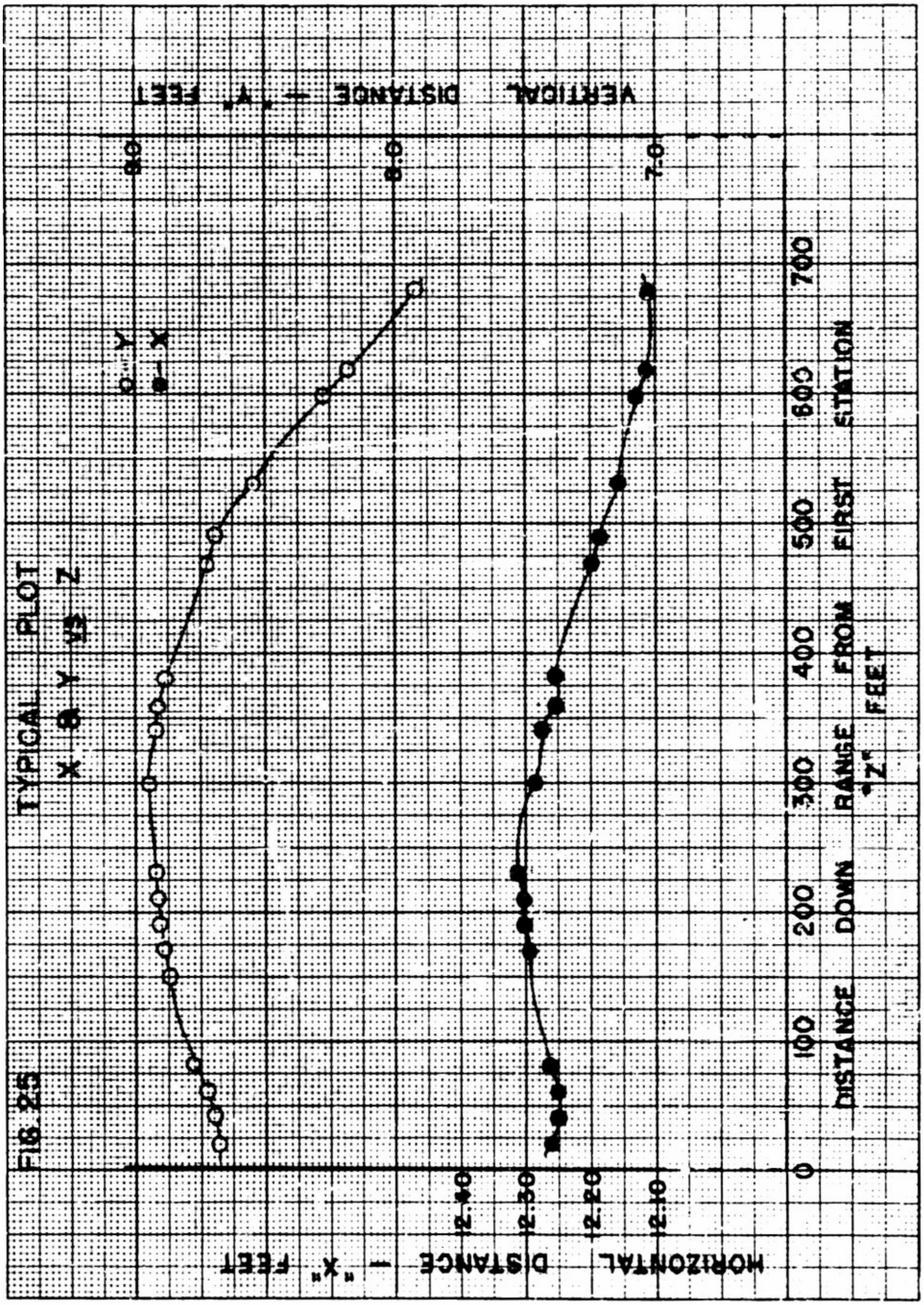

TYPICAL PLOT
X & Y VS Z
O - Y
● - X
VERTICAL DISTANCE — "Y" FEET
7.0
HORIZONTAL DISTANCE — "X" FEET
12.40
12.30
12.20
12.10
0
100
200
300
400
500
600
700
DISTANCE DOWN RANGE FROM FIRST STATION
"Z" FEET

FIG. 25

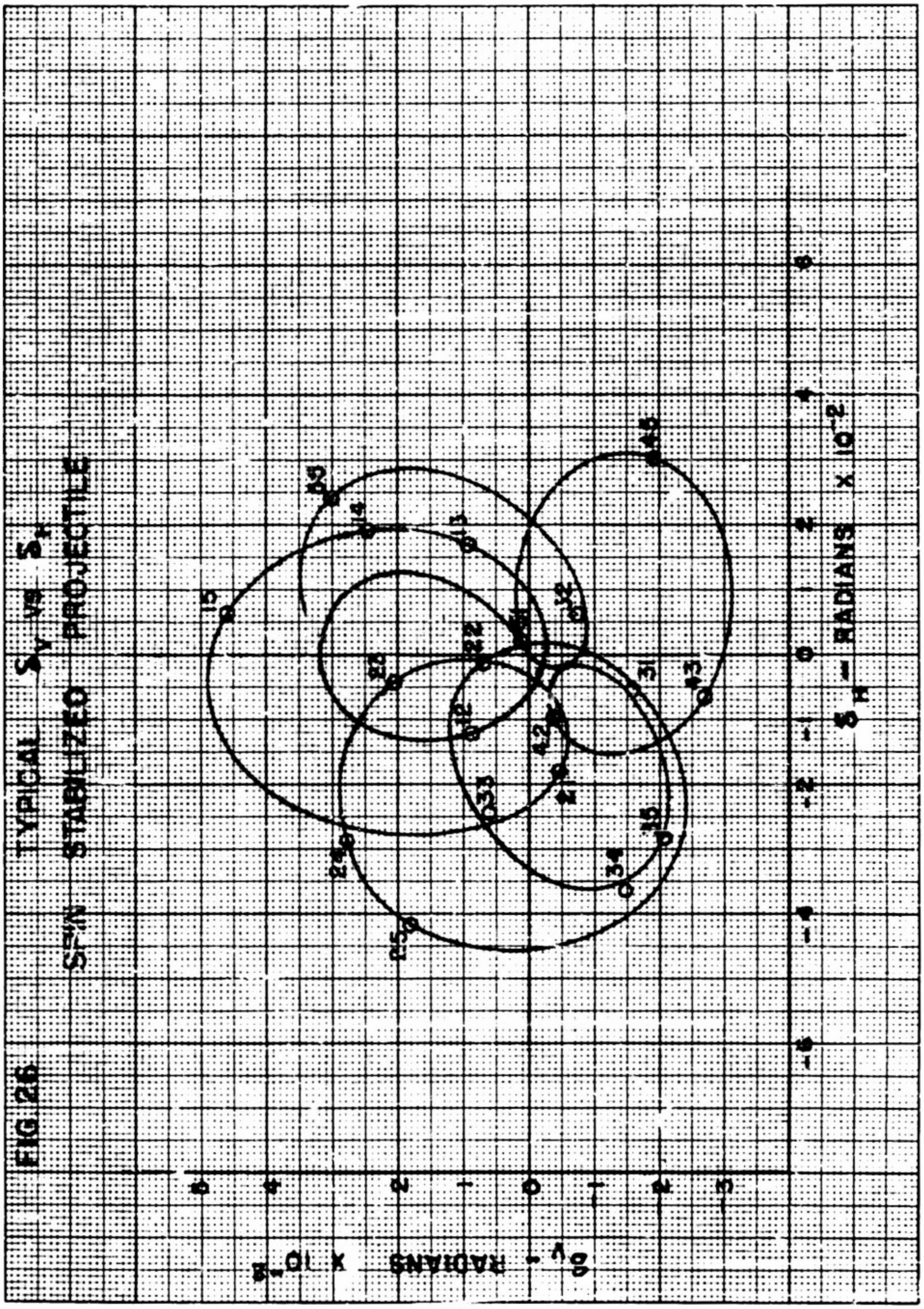


FIG. 26 TYPICAL δ_V vs δ_H SPIN STABILIZED PROJECTILE

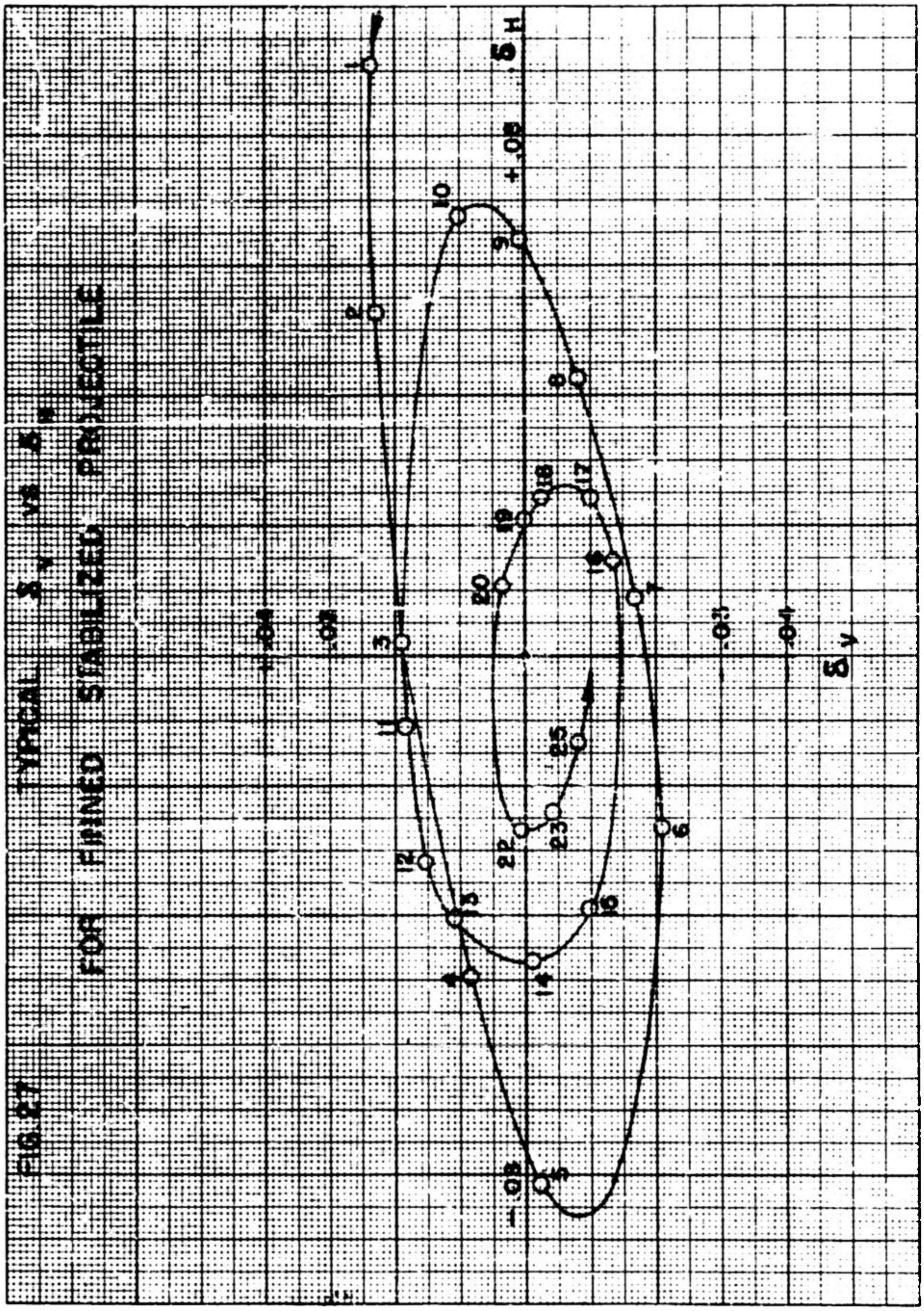


FIG. 27 TYPICAL δ_V VS δ_H FOR FINNED STABILIZED PROJECTILE

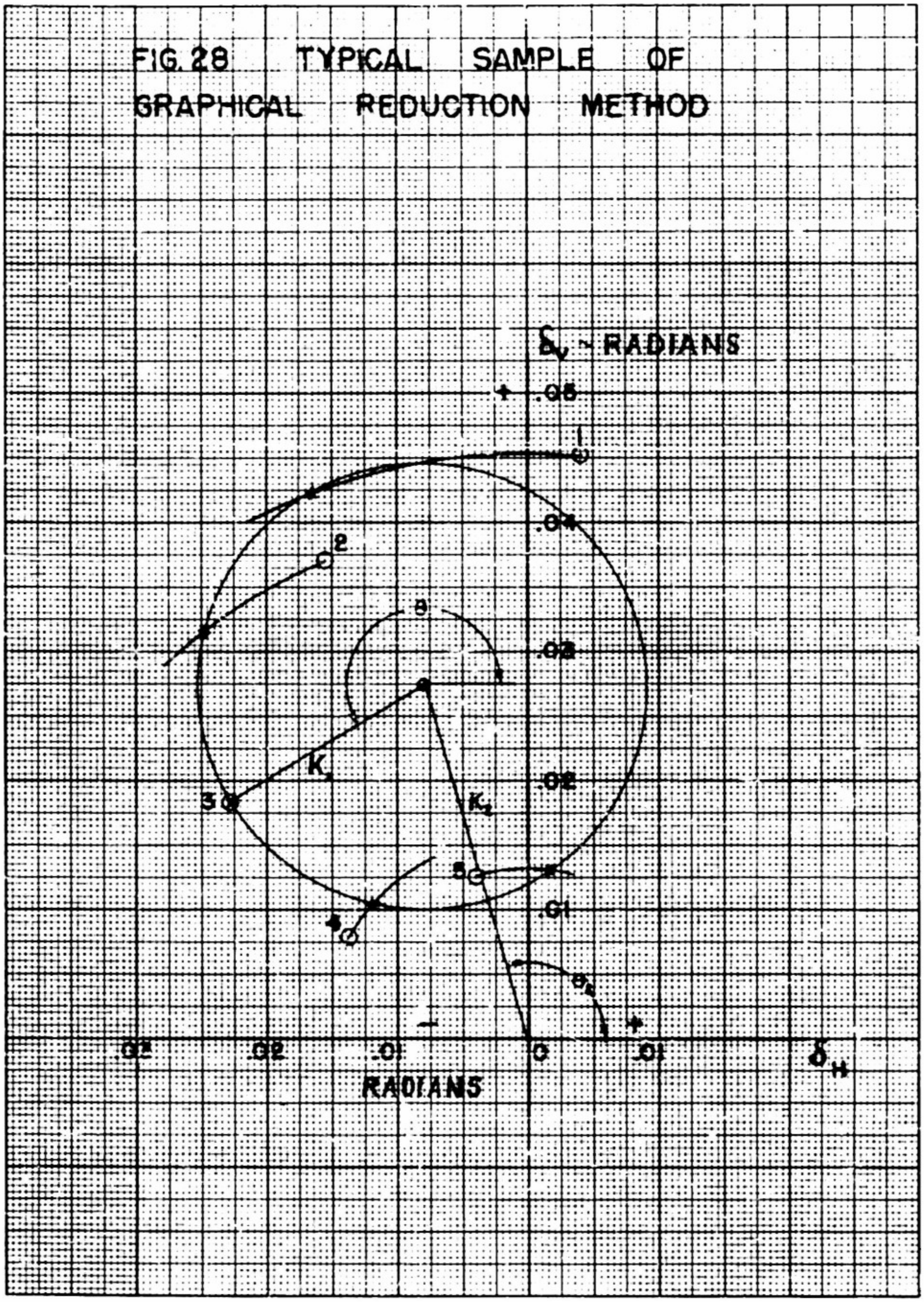
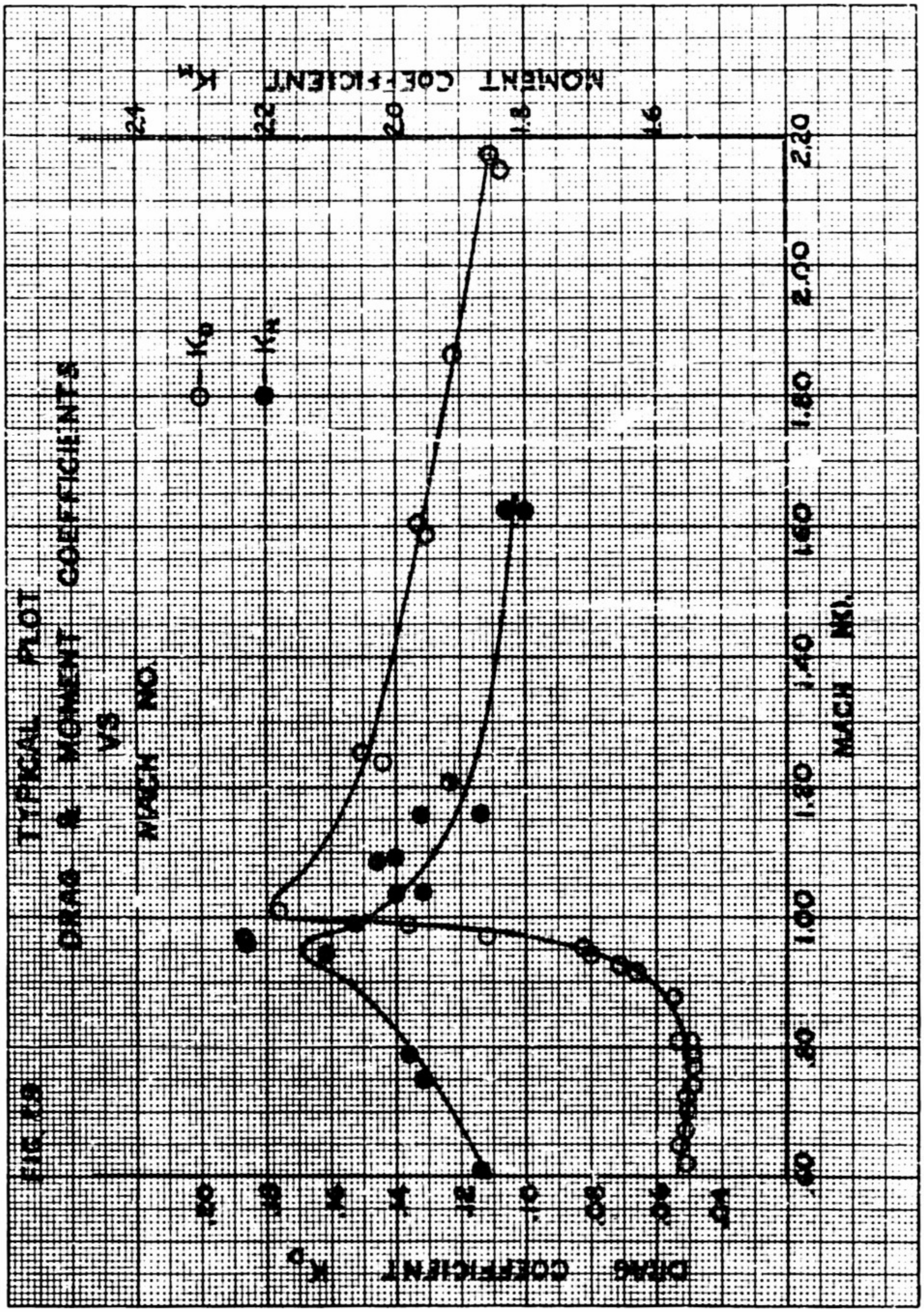


FIG. 28 TYPICAL SAMPLE OF
GRAPHICAL REDUCTION METHOD
δ_V ~ RADIANS
+ .05
.04
.03
.02
.01
1
2
3
4
5
θ
θ_2
K_1
K_2
−
+
.03
.02
.01
0
.01
δ_H
RADIANS



TYPICAL PLOT
DRAG & MOMENT COEFFICIENTS
VS
MACH NO.
MOMENT COEFFICIENT K_M
24
22
2.0
1.8
1.6
DRAG COEFFICIENT K_D
.20
.18
.16
.14
.12
.10
.08
.06
.04
MACH NO.
.60
.80
1.00
1.20
1.40
1.60
1.80
2.00
2.20
K_D
K_M

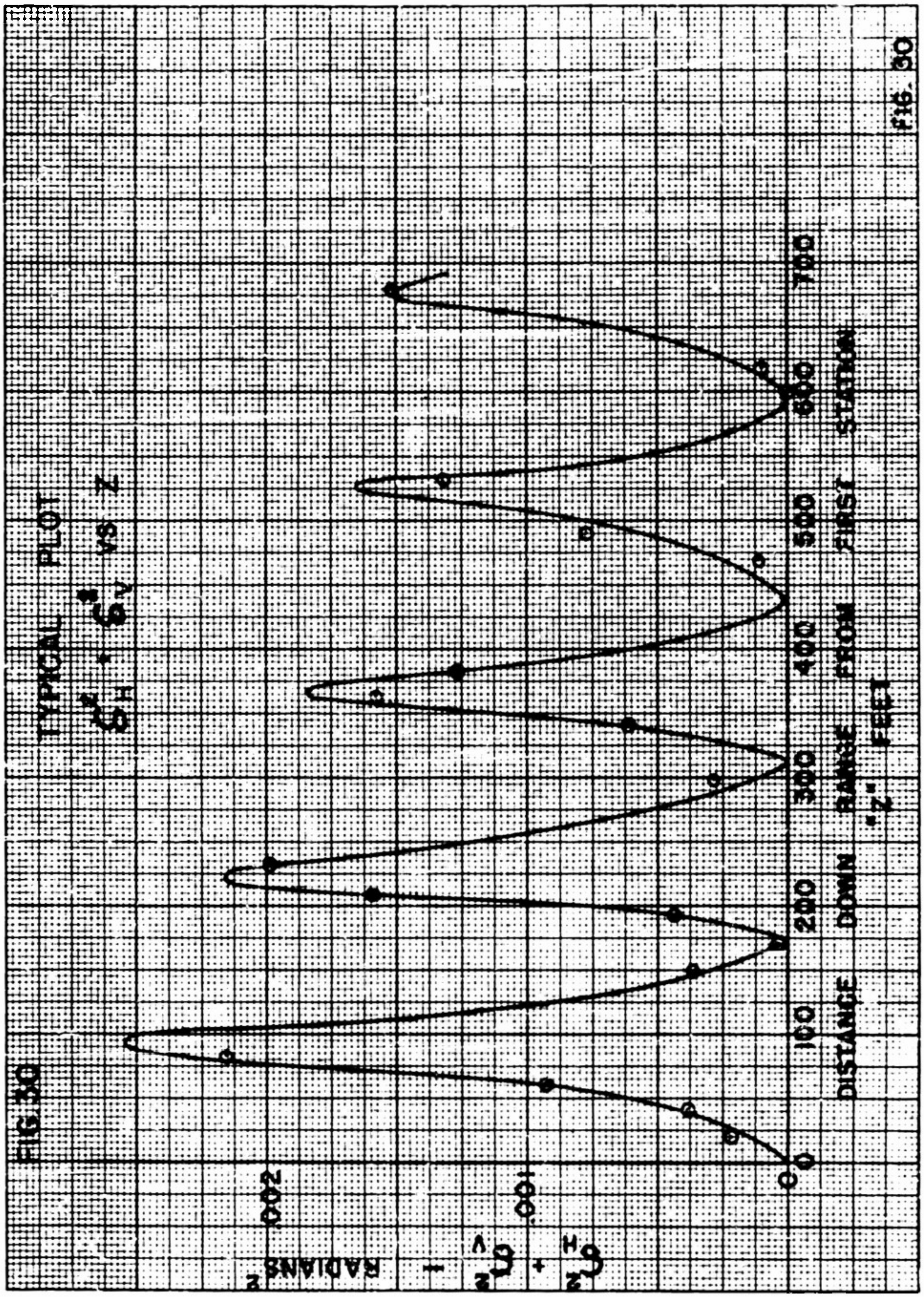


FIG 30
TYPICAL PLOT
$\xi_H^2 + \xi_V^2$ VS Z
0
100
200
300
400
500
600
700
DISTANCE DOWN RANGE FROM FIRST STATION
"Z" FEET
.001
.002
$\xi_H^2 + \xi_V^2$ — RADIANS²
FIG. 30

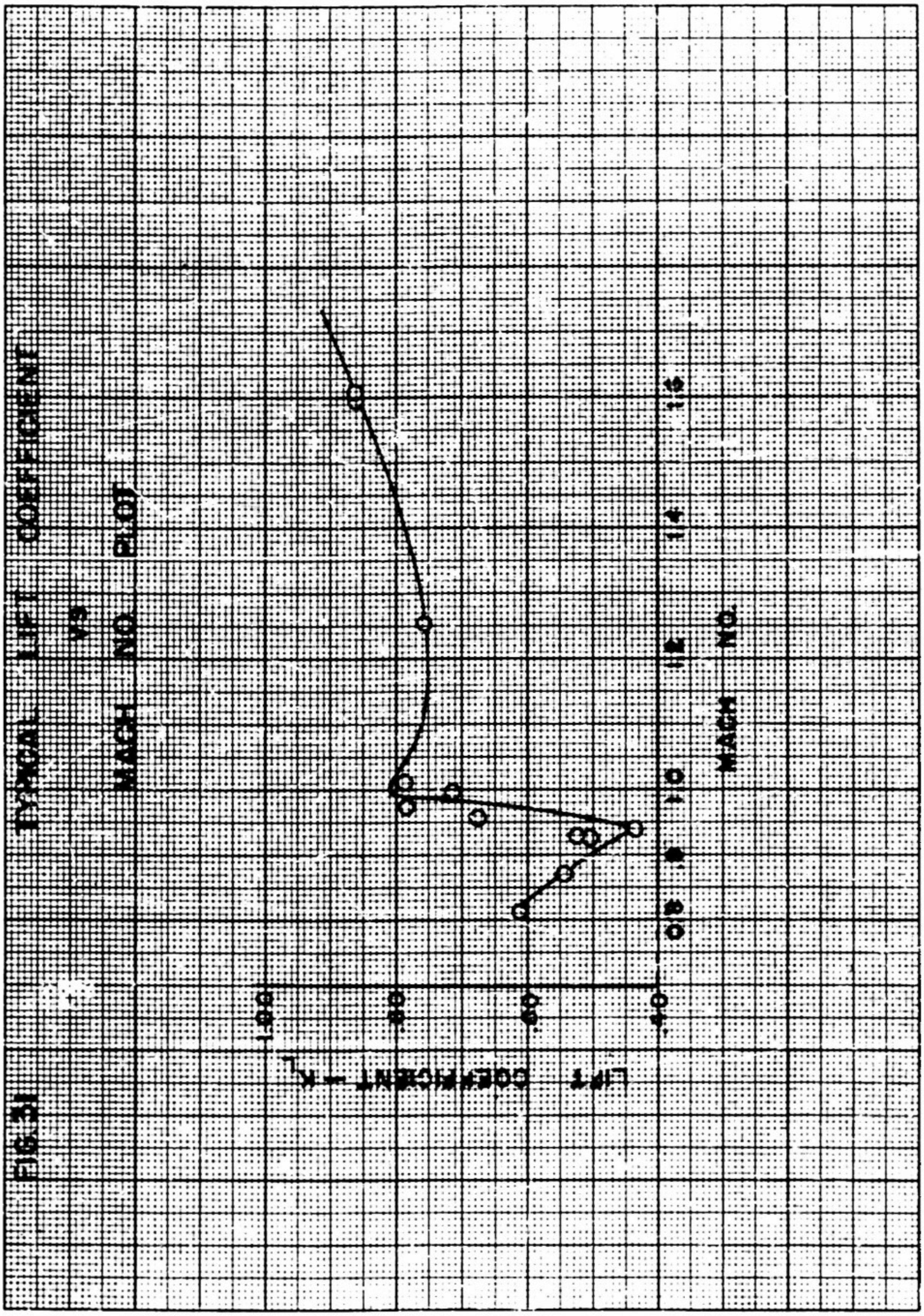


FIG. 31
TYPICAL LIFT COEFFICIENT
VS
MACH NO. PLOT
LIFT COEFFICIENT — K_L
1.00
.80
.60
.40
.8
1.0
1.2
1.4
1.6
MACH NO.

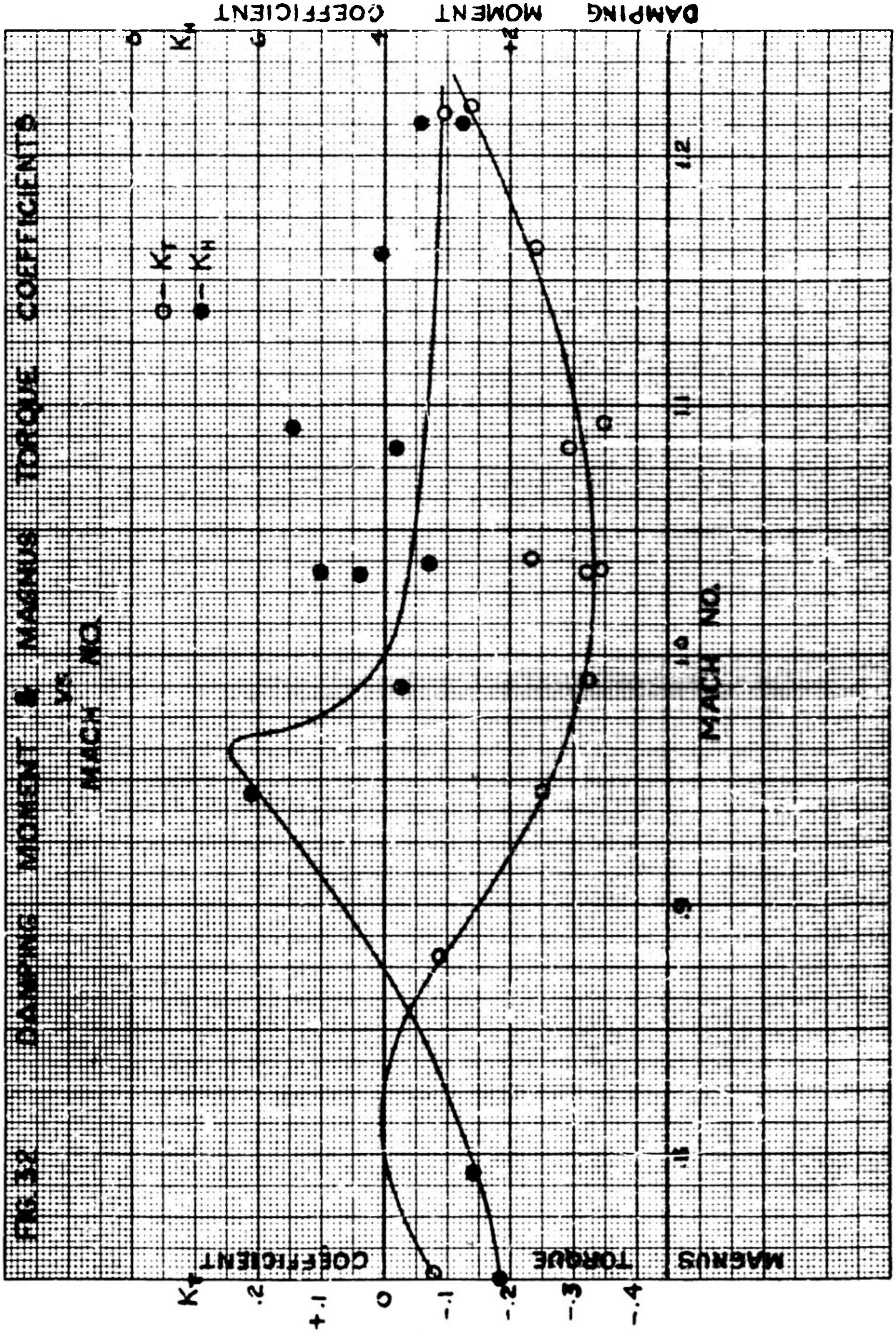


FIG. 32 DAMPING MOMENT & MAGNUS TORQUE COEFFICIENTS vs. MACH NO.